Wind-US User's Guide[*]

The NPARC Alliance

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[*] This document describes the use of Wind-US Version 1.0, and was created December 5, 2007. It was originally based on the 24 Jan 1997 version of the *NASTD User's Guide*, by R. H. Bush, M. Mani, T. R. Michal, and W. W. Romer of McDonnell Douglas Aerospace. Please send documentation suggestions/corrections to Charlie Towne at *towne@grc.nasa.gov*. Questions about Wind-US itself or the NPARC Alliance should be sent to *nparc-support@info.arnold.af.mil*, (931) 454-7885

Contents

1 Introduction

This manual describes the operation and use of Wind-US, a computational platform which may be used to numerically solve various sets of equations governing physical phenomena. Wind-US represents a merger of the capabilities of four CFD codes — NASTD (a structured grid flow solver developed at McDonnell Douglas, now part of Boeing), NPARC (the original NPARC Alliance structured grid flow solver), NXAIR (an AEDC structured grid code used primarily for store separation analysis), and ICAT (an unstructured grid flow solver developed at the Rockwell Science Center and Boeing).[1] Currently, the code supports the solution of the Euler and Navier-Stokes equations of fluid mechanics, along with supporting equation sets governing turbulent and chemically reacting flows.

1.1 Mathematical Model

All terms are retained in the governing equations, including secondary flow, reversed flow convection, pressure gradients normal to a wall, streamwise diffusion, and unsteady flow. All heat transfer terms are retained. Several algebraic, one-equation, and two-equation turbulence models are available. Transition may be specified through the use of an external file. Modification of the effective heat transport coefficient due to turbulence is linked to the momentum diffusion coefficient by a turbulent Prandtl number, which is taken to be constant.

The fluid may be treated as a thermally and calorically perfect gas, a thermally perfect gas, equilibrium air, or a mixture undergoing a finite rate chemical reaction. For ideal gas, conventional values are given to the gas constant (R) and the ratio of specific heats (γ), or they may be specified.

1.2 Geometry and Mesh Description

Wind-US uses externally generated computational grids. Therefore, all geometric input and capability depend on the grid generator. Wind-US has no geometric input. All analyses must be preceded by a grid generation run.

Wind-US uses multi-zone computational grids, and is capable of computing solutions on a wide variety of structured or unstructured grids. However, not all of the features of Wind-US are available for both types of grids. The individual keyword descriptions note when a specific capability is limited to structured or unstructured grids.

Because Wind-US is written to accommodate arbitrary grid topologies and boundary condition combinations, it may be used to obtain solutions about most of the geometric configurations for which a grid can be generated. The multi-zone approach makes it possible to decompose virtually any configuration into a number of manageable subregions, or zones. Zonal connectivity information is computed using a pre-processing code (either GMAN or MADCAP), and stored in the grid file used by Wind-US. During the course of a solution, Wind-US maintains continuity in flow properties across zone boundaries through a process known as zone coupling (Romer and Bush, 1993).

[1] Wind-US is a product of the NPARC Alliance, a partnership between the NASA Glenn Research Center (GRC) and the USAF Arnold Engineering Development Center (AEDC) dedicated to the establishment of a national, applications-oriented flow simulation capability. The Boeing Company has also been closely associated with the Alliance since its inception, and represents the interests of the NPARC User's Association.

1.3 Numerical Technique

The solution is executed iteratively on the computational mesh. The flow equations are evaluated using second-order-accurate finite differences. The partial differential equations are modeled in their conservative form. Explicit terms are computed using either upwind or central differencing, and their order may be controlled through the use of keywords in the input data file. The implicit terms are computed using either an approximately factored or four-stage Runge-Kutta scheme, or they may be disabled altogether. A Global Newton iteration scheme is also available, and may be used for unsteady flows with large time scales or as a convergence acceleration technique for steady flows.

1.4 Coding

Wind-US is written almost entirely in ANSI Standard Fortran 90. The low-level library routines are generally written in Fortran 77 and/or in ANSI C. The production version of the code is supported on a variety of systems from Silicon Graphics, Hewlett-Packard, Sun, and Cray.

2 Tutorial

This section is intended primarily for new users to demonstrate the simulation process using Wind-US. More experienced users may find this section useful as a road map through the simulation process and to help demonstrate new features. The approaches presented here are by no means unique, and detailed information is excluded by design. The user is referred to later sections of this User's Guide for more detailed information on the various aspects of running Wind-US, and in particular to Section 10 for more in-depth discussions on the choices available for each input keyword.

The approach taken here is to discuss the flow simulation process using as an example a simple subsonic internal flow in a diverging duct. The various files discussed in this section may be downloaded from the Wind-US documentation WWW site, at http://www.grc.nasa.gov/WWW/winddocs/user/tutorial.html#tutorial:downloading.

While it is clearly impossible to demonstrate every option in Wind-US with a single application, the basic mechanics of using Wind-US are demonstrated with this case. Additional abbreviated examples are also provided in Section 10 for specific keywords. For details of the flow simulation process for more complex cases, please see the various example applications accessible from the Wind-US Validation home page at `http://www.grc.nasa.gov/WWW/wind/valid/validation.html`.

The solution process using any conventional time-marching Navier-Stokes code is basically the same, and may be divided into the following steps:

- Gather information
- Create the computational grid
- Define the input
- Run the code
- Monitor convergence
- Examine the results

The mechanics of doing each of these steps may vary from code to code, however. The following sections describe how these steps are typically accomplished when using Wind-US.

2.1 Gather Information

As for any project, the first step is to gather all of the information required to completely specify the problem to be analyzed. Of course, as the flow simulation process proceeds, missing information will become apparent. The required information can be divided into three major categories — geometry, flow conditions, and boundary conditions. It is also important to understand the ultimate goal of the simulation. For example, is an accurate drag prediction required? Or, is lift required, but only to within 5%? The answers to these types of questions will determine the detail of the input information required to provide the necessary level of detail and accuracy in the solution.

2.1.1 Geometry

The more geometric details that can be determined for the target application, the more likely the results will provide an accurate simulation of the flow field. This is not to say that all geometric components must be modeled. Resolving fine geometric details of a configuration requires more grid points, and, as a result, longer run times. The level of detail to which the geometry must be modeled depends on the type of results required and the acceptable turn-around time.

The geometry of the Test Case 4 example is shown in Figure 1. The duct is 8 inches long, and the entrance and exit heights are 1 inch and 2 inches, respectively.

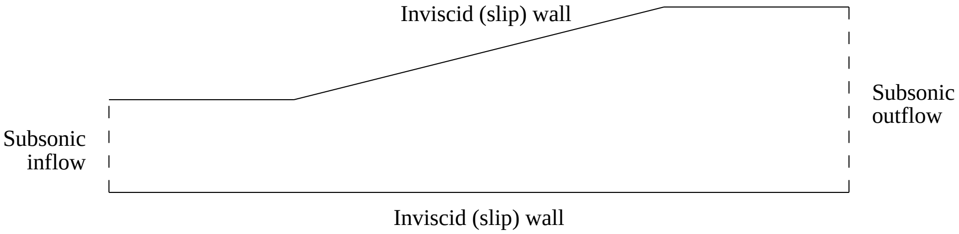


Figure 1: Test case geometry

The desired result from this calculation is the pressure distribution along the upper and lower walls, and the mass flow rate to within 10%. Thus, resolving the sharp surface gradients at the corners is not necessary. Other detailed geometric features such as weld joints, for example, are also not modeled. If the fine details of the boundary layer in the vicinity of the joints were important, then a significantly more detailed geometry description would be required.

2.1.2 Flow Conditions

In addition to the geometric information, flow conditions are also required, and are used to set the reference conditions used in non-dimensionalizing the governing equations solved by Wind-US. As with the geometric information, the simulation results will only be as good as the flow condition information provided by the user. Flow conditions should be specified that are representative of the flow being solved, so that the nondimensional variables used in the code are on the order of 1.0. A good choice is the inlet conditions for internal flows, and the freestream conditions for external flows.

For this example case, the inlet Mach number, total pressure, and total temperature are 0.78, 15 psi, and 600 °R, respectively. Starting from these conditions, the Reynolds number based on the duct height may be computed as 3.023×10^5.

2.1.3 Boundary Conditions

Information is also required at boundaries that are at the "outer edges" of the computational domain. These boundary conditions are used to model the interaction between the flow inside the computational domain and surfaces or flows outside the domain. In fact, the boundary conditions are perhaps the most important factor influencing the accuracy of the flow computation.

Conditions at flow interface boundaries — boundaries between flows inside and outside the computational domain such as inflow, outflow, and freestream boundaries — must be known to the level of accuracy required by the simulation. For example, if flow rates are required to within 0.1%, even slight variations in total pressure at the inflow boundary must be specified. The number of conditions to be specified at a flow interface boundary depends on whether the flow is entering or leaving the computational domain, and whether it is subsonic or supersonic.

Information must also be specified at surface interface boundaries, such as solid walls and bleed regions. Simply specifying the type of boundary, such as an adiabatic no-slip wall, is often sufficient. Additional information may also be required, though, such as the wall temperature. The level of detail that is needed for this information is determined, as discussed above, by the level of detail and accuracy required in the results.

Note that other types of boundaries may be present within the overall computational domain, that are not at the "outer edges." Multi-zone problems will have zonal interface boundaries. Some configurations will also have boundaries resulting from the grid topology, such as self-closing and singular axis boundaries. These types of boundaries need only be labeled.

For Test Case 4 the flow at both the inflow and outflow planes will be subsonic. Three conditions are needed at the inflow boundary, and one is needed at the outflow boundary. At the inflow boundary, uniform flow is specified, with total pressure and temperature equal to the inlet values of 15 psi and 600 °R. Since extreme accuracy in the solution is not needed, constant total conditions at the inflow are sufficient. At the outflow boundary, the exit static pressure is set to 14.13 psi. The Reynolds number for Test Case 4 is large enough that the boundary layers will have little influence on the pressure distribution within the duct. The upper and lower boundaries are therefore specified as inviscid (slip) walls.

In this tutorial, the procedure used to set boundary conditions when running Wind-US is discussed in Section 2.3.2. Additional details on all the boundary conditions available in Wind-US are presented in Section 5.

2.2 Create the Computational Grid

Wind-US uses externally-generated grids. The grids for all the zones must therefore be created before running Wind-US. The geometry of the application governs the overall shape of the boundaries, but the approach to gridding the flow field is not unique.

2.2.1 General Requirements

The Wind-US flow simulator provides considerable flexibility. Grid lines can conform to complex shapes or may pass through regions not in the flow field. The grid may be divided into zones to conform to the geometry better, to allow grid embedding (i.e., zones with finer grids in regions of high gradients like boundary layers), and/or to allow parallel computation. These zones may be abutting or overlapping, and overlapping grids may be single- or double-fringed.

Wind-US can compute flows using structured or unstructured grids. In this tutorial a structured grid is used. The indices (i, j, k) thus represent a curvilinear coordinate system, and physical Cartesian coordinates (x, y, z) are defined for each integer combination of indices. The handedness of both the physical and curvilinear coordinate systems is required to be the same at all points in the grid, i.e., both must be either left-handed or right-handed. Additionally, at least three grid points must fall between any two grid lines which represent a boundary within the computational domain. For example, if the $k = 1$ boundary represents a solid surface and an adjacent k boundary represents a symmetry plane, the symmetry plane must be at $k = 5$ or higher, so that the three points $k = 2$, 3, and 4 (at least) lie between the two boundaries.

The method used to create the grid is completely up to the user. For complex geometries, a sophisticated grid generation program is normally used. For very simple geometries, it may be easier to write a short program that constructs a grid using algebraic techniques.

2.2.2 Creating the Common Grid (*.cgd*) File

The computational grid used by Wind-US for a particular case is stored in a *Common Grid* (*.cgd*) file, so named because the file is formatted according to Boeing's Common File Format.[2] The (x, y, z) coordinates of all the grid points, zone coupling information, grid units, and scaling data are stored in this file.[3]

Since some grid generation codes do not produce *.cgd* files directly, a separate utility called *cfcnvt* is included with Wind-US that may be used to convert a variety of file formats, including PLOT3D files, to Common Files. A typical procedure is thus to first store the grid file as a PLOT3D xyz file, which is an available option in most general-purpose grid generation codes, and then convert it to a *.cgd* file using *cfcnvt*.

Zone coupling information is then added to the *.cgd* file using either the GMAN or MADCAP pre-processing utility. This is typically done at the same time as the boundary condition types are defined, and is discussed in Section 2.3.2. The *.cgd* file may then be examined to assess grid quality and list information about the points and zones in the grid. GMAN or MADCAP may also be used to generate the interior grid itself, given the grids on the zonal boundaries. Descriptions of these capabilities, and others, may be found in the user's guides for GMAN and MADCAP

2.2.3 Test Case 4 Grid

The computational grid for Test Case 4 was constructed by simple algebraic techniques using the following program, called *case4.mesh.f*, which creates a PLOT3D xyz file in 2-D unformatted multi-zone form to Fortran unit 2, without an `iblank` array.

```
      Program mesh
c
c-----Purpose:  This subroutine computes a 2-D three-zone grid for a
c               simple diffuser, one of the test cases supplied with
c               Wind-US.  The grid is written to a file in PLOT3D 2-D
c               unformatted multi-zone form, without iblank'ing.
c
c-----Called by:
c
c-----Calls:
c
      Implicit none
c-----Parameter statements
      Integer IDIM,JDIM    ! Max dimensions
      Integer NBLKS        ! Number of blocks
      Parameter (IDIM = 33, JDIM = 11)
      Parameter (NBLKS = 3)
c-----Local variables:
      Integer i,j          ! Indices in x and y directions
      Integer iblk         ! Current block number
      Integer imax(NBLKS),jmax(NBLKS)   ! Block grid sizes
      Real dx(NBLKS),dy(NBLKS)        ! Non-dim grid increments in blks
      Real x(IDIM,JDIM),y(IDIM,JDIM),z(IDIM,JDIM)   ! Grid coordinates
```

[2] Wind-US also supports the use of CGNS files for the grid and flow solution, using the `CGNSBASE` keyword. This tutorial, however, uses common files.

[3] See the *Common File User's Guide* for details about the internal structure of common files.

```
      Real xdiff1,xdiff2   ! x at start/end of diffuser section
      Real xloc            ! Local x coordinate
      Real xmax            ! x at end of duct
      Real xstrt(NBLKS),xend(NBLKS)   ! Non-dim x limits of blocks
      Real ymax            ! Max y at x = xloc
      Real ymax1,ymax2     ! Max y at start/end of diffuser section
      Real yslope          ! Slope of diffuser upper wall
      Real ystrt(NBLKS),yend(NBLKS)   ! Non-dim y limits of blocks
c
c-----Define geometric parameters
c
      Data xdiff1,xdiff2,xmax /2.0, 6.0, 8.0/
      Data ymax1,ymax2 /1.0, 2.0/
c
c-----Set relative sizes and grid increments for each block
c
c-----Block 1
      imax(1) = 17
      jmax(1) =  6
      xstrt(1) = 0.0
      ystrt(1) = 0.0
      xend (1) = 0.5
      yend (1) = 0.5
      dx(1) = (xend(1) - xstrt(1))/(imax(1) - 1)
      dy(1) = (yend(1) - ystrt(1))/(jmax(1) - 1)
c-----Block 2
      imax(2) = 33
      jmax(2) = 11
      xstrt(2) = 0.0
      ystrt(2) = yend(1)
      xend (2) = xend(1)
      yend (2) = 1.0
      dx(2) = (xend(2) - xstrt(2))/(imax(2) - 1)
      dy(2) = (yend(2) - ystrt(2))/(jmax(2) - 1)
c-----Block 3
      imax(3) = 17
      jmax(3) = 11
      xstrt(3) = xend(1)
      ystrt(3) = 0.0
      xend (3) = 1.0
      yend (3) = 1.0
      dx(3) = (xend(3) - xstrt(3))/(imax(3) - 1)
      dy(3) = (yend(3) - ystrt(3))/(jmax(3) - 1)
c
c-----Open grid file, write header info
c
      Open (unit=2, file='fort.2', form='unformatted')
      Write (2) NBLKS
      Write (2) (imax(iblk),jmax(iblk),iblk=1,NBLKS)
c
c-----Construct the grid
```

```
c
      yslope = (ymax2 - ymax1)/(xdiff2 - xdiff1)   ! Slope of diff wall
      Do 100 iblk = 1,NBLKS       ! Loop over no. of blocks
         Do 50 i = 1,imax(iblk)   ! Loop over no. of x points
c-----------Compute x coordinates
            xloc = (xstrt(iblk) + dx(iblk)*(i-1))*xmax
            Do 10 j = 1,jmax(iblk)   ! Loop over no. of y points
               x(i,j) = xloc
10          Continue
c-----------Get local max y, then compute y coordinates
            If (xloc .le. xdiff1) then        ! Upstream of diffuser
               ymax = ymax1
            Else if (xloc .ge. xdiff2) then   ! Downstream of diffuser
               ymax = ymax2
            Else                              ! In diffuser
               ymax = ymax1 + yslope*(xloc-xdiff1)
            End if
            Do 20 j = 1,jmax(iblk)   ! Loop over no. of y points
               y(i,j) = (ystrt(iblk) + dy(iblk)*(j-1))*ymax
20          Continue
50       Continue
c
c-----Write the grid file in PLOT3D xyz format
c
         Write (2) ((x(i,j),i=1,imax(iblk)),j=1,jmax(iblk)),
     &             ((y(i,j),i=1,imax(iblk)),j=1,jmax(iblk))
100   Continue
      Stop
      End
```

Figure 2 shows the resulting grid. Three zones are used, with grid sizes of 17 × 6, 33 × 11, and 17 × 11, respectively.[4]

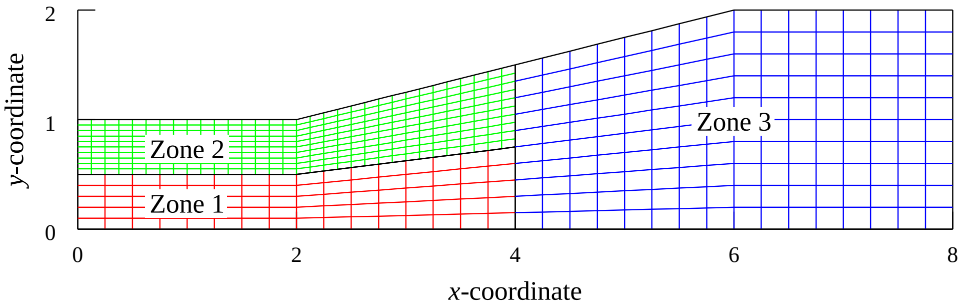


Figure 2: Test case grid

The grid file written by the above program, named *case4.xyz*, was converted to a *.cgd* file named *case4.cgd* using *cfcnvt*, as shown in the following runstream. Lines in slanted type were typed by the user.

[4] This geometry is simple enough that a single-zone grid would be sufficient, but a three-zone grid is used for illustrative purposes.

```
cfcnvt
 ****************************************************************************
 * Warning: This software contains technical data whose export is           *
 * restricted by the Arms Export Control Act (Title 22, U.S.C., Sec 2751,   *
 * et seq.) or Executive Order 12470. Violation of these export-control     *
 * laws is subject to severe criminal penalties. Dissemination of this      *
 * software is controlled under DoD Directive 5230.25 and AFI 61-204.       *
 ****************************************************************************
          ******* Common File Convert Utilities ******
 CFCNVT - Version 1.45 (last changed 2001/12/14 18:24:56)

   0: Exit program
   2: Import   a Common File
   3: Compress a Common File
   4: Break Common File into multiple transfer files
   5: Combine multiple transfer files into Common File
   6: Append one Common File to another
   7: Convert Common File binary to a text file
   8: Convert Common File text to a binary file
  11: Convert PLOT3D/Pegsus file to Common File
  12: Convert GASP     file to Common File
  13: Convert OVERFLOW file to Common File
  14: Convert Common File to OVERFLOW file
  15: Convert CFPOST GPU file to Common File GPC
  16: Convert ascii rake to Common File rake CGF
  17: Convert Pegsus 4.0 files to Common File

  Enter the number from one of the above requests
11

   PLOT3D file type menu

   0: Main menu
   1: Convert a PLOT3D Grid     (.x) file to CFS.
   2: Convert a PLOT3D Solution (.q) file to CFS.
   3: Convert a PLOT3D Function (.f) file to CFS.

  Enter the number from one of the above requests
1

   PLOT3D Number of Grids menu

   0: Main menu
   1: PLOT3D Single zone format.
   2: PLOT3D Multi  zone format.

  Enter the number from one of the above requests
2

   PLOT3D Zone dimension menu
   0: Main menu
   1: PLOT3D 2d zone format.
   2: PLOT3D 3d zone format.

  Enter the number from one of the above requests
1

   PLOT3D Format menu

   0: Main menu
   1: PLOT3D Formatted   (ASCII).
   2: PLOT3D Unformatted (sequential binary).
   3: PLOT3D Binary (c binary).

  Enter the number from one of the above requests
2

   PLOT3D Iblank menu

   0: Main menu
   1: PLOT3D grid with    IBLANK format.
   2: PLOT3D grid without IBLANK format.

  Enter the number from one of the above requests
2

   PLOT3D Precision menu

   0: Main menu
   1: PLOT3D Single precision format.
   2: PLOT3D Double precision format.

  Enter the number from one of the above requests
1

   PLOT3D INTOUT menu

   0: Main menu
   1: No INTOUT/XINTOUT file.
   2: INTOUT file.
   3: XINTOUT file.

  Enter the number from one of the above requests
1
  Enter PLOT3D .x file to convert with suffix
case4.xyz
  Enter output Common File name with suffix
case4.cgd
  Global maximums set as follows:
  mimax 33
  mjmax 11
  mkmax 1
  mpts: 363
  recl: 726
 Processing zone ZONE   1
 Writing mesh data
 Processing zone ZONE   2
 Writing mesh data
 Processing zone ZONE   3
 Writing mesh data

   0: Exit program
   2: Import   a Common File
   3: Compress a Common File
   4: Break Common File into multiple transfer files
   5: Combine multiple transfer files into Common File
   6: Append one Common File to another
   7: Convert Common File binary to a text file
   8: Convert Common File text to a binary file
  11: Convert PLOT3D/Pegsus file to Common File
  12: Convert GASP     file to Common File
  13: Convert OVERFLOW file to Common File
  14: Convert Common File to OVERFLOW file
  15: Convert CFPOST GPU file to Common File GPC
  16: Convert ascii rake to Common File rake CGF
  17: Convert Pegsus 4.0 files to Common File

  Enter the number from one of the above requests
0
```

2.3 Define the Input

The next step is to define the input data. Input is required to specify the flow and initial conditions, the boundary conditions, and various parameters controlling the physical and numerical models to be used when running the code.

The primary file controlling how Wind-US is executed is the *Input Data* (*.dat*) file. With many CFD codes the input data are specified using Fortran namelist and/or formatted input. With Wind-US, the input is specified using descriptive keywords. The formatting rules for the *.dat* file are described in Section 7.1.

This section is intended as an introduction to some of the more commonly-used keywords. After reading the information presented here, a new user should supplement it with the detailed information in Section 10. For many cases, the default values for the various keyword options are acceptable, but users should become familiar with all of the options for the most effective use of Wind-US.

2.3.1 Descriptive Header and Comments

The first three lines of the file are reserved for geometry, flow condition, and arbitrary titles, respectively. Each of these titles may be up to 64 characters long.

Comment lines, beginning with a `/`, may be placed anywhere in the file after the first three lines.

The readability of the *.dat* file may be improved significantly through the liberal use of comments — for example, to separate logical sections of the data file like boundary conditions, numerical operators, convergence monitoring parameters, etc.

2.3.2 Boundary Conditions

With most CFD codes, boundary conditions are completely specified in the input data file. With Wind-US, however, setting boundary conditions is a two-step process, defining first the *type* of boundary, and then any *values* that are needed.

The first step is to label each boundary of each zone with the *type* of boundary condition to use, such as "viscous wall," "outflow," or "coupled." This is done using either the GMAN or MADCAP pre-processing code, and the information is stored in the Common Grid (*.cgd*) file. Details on the boundary condition types available for use with Wind-US are in Section 5 and in the *GMAN User's Guide*.

Boundary condition types may be specified for all or part of a boundary, allowing multiple boundary conditions on a single boundary.

"Coupled" zonal interface boundaries do not have to be explicitly labeled by the user. Both GMAN and MADCAP can automatically examine the grid to find them and determine the zones involved, compute the geometric interpolation factors, and store the information in the *.cgd* file. GMAN or MADCAP is also used to cut holes and generate interpolation coefficients for overlapping (”chimera”) boundaries. The process is currently not completely automated for chimera boundaries.

The second step is to define any *values* needed for a particular boundary condition, such as an exit pressure or a bleed rate. This information is specified in the *.dat* file. Keywords are available to specify conditions at inflow boundaries (`ARBITRARY INFLOW`), at outflow boundaries (`COMPRESSOR FACE`, `DOWNSTREAM MACH`, `DOWNSTREAM PRESSURE`, `MASS FLOW`), along solid walls (`MOVING WALL`, `TTSPEC`, `WALL TEMPERATURE`), in bleed and blowing regions (`BLEED`, `BLOW`), and across actuators and screens (`ACTUATOR | SCREEN`).

2.3.3 Flow and Initial Conditions

The flow conditions (Mach number, and static or total pressure and temperature, plus the angles of attack and yaw) are specified using the `FREESTREAM` keyword. These conditions, along with a reference length based on the units used in the *.cgd* file, are used as the reference conditions and determine the Reynolds number.

The usual procedure with Wind-US is to start a new problem by setting the initial conditions at each grid point equal to the values specified using the `FREESTREAM` keyword. Other keywords allow different values to be used in different zones (`ARBITRARY INFLOW`), a boundary layer to be added along a specified surface in a zone (`BL_INIT`), and reinitialization of the flow in specified zones after a restart (`REINITIALIZE`). Previously-run, partially-converged cases will normally be restarted using the current solution as initial conditions (`RESTART`). More information about flowfield initialization may be found in Section 3.6.

2.3.4 Physical Model Controls

Dimensionality. Wind-US may be used for three-dimensional, two-dimensional, quasi-three-dimensional, or axisymmetric configurations. Internally, Wind-US treats the grid as three-dimensional, with indices i, j, and k. Two-dimensional cases simply have $k_{max} = 1$, with the i-j grid lying in a nonzero, constant z plane. The effect of area variation in an otherwise two-dimensional configuration may be modeled using Wind-US's quasi-three-dimensional capability, which is activated by setting the z-coordinate equal to the "width" of the geometry at each grid point. Axisymmetric configurations are modeled using a two-dimensional grid in conjunction with the `AXISYMMETRIC` keyword. More details may be found in Section 3.1.

Flow Equations. The default equations solved by Wind-US are the full Reynolds-averaged Navier-Stokes equations. Keywords are available to solve the Euler equations (`TURBULENCE`), parabolized Navier-Stokes equations (`MARCHING`), or the thin-layer Navier-Stokes equations (`TSL`). See Section 4.2.2 for more information about the thin-layer option.

Turbulence Model. A variety of turbulence models are available in Wind-US through the `TURBULENCE` keyword. These include the Baldwin-Lomax, Cebeci-Smith, and P. D. Thomas algebraic models; the Spalart-Allmaras and Baldwin-Barth one-equation models; and the Chien k-ϵ, Rumsey-Gatski k-ϵ algebraic Reynolds stress, and Menter Shear Stress Transport (SST) two-equation models.[5] A laminar flow option is also available using the `TURBULENCE` keyword, and a laminar-turbulent transition region may be modeled using the `TTSPEC` keyword. See Section 3.3 for more information.

Gas Model and Chemistry. A variety of gas models are available in Wind-US to complete the equation set. The fluid may be treated as a thermally and calorically perfect gas, a thermally perfect gas (frozen chemistry), equilibrium air, or a mixture undergoing a finite rate chemical reaction. For a thermally and calorically perfect gas, the values of γ, the laminar and turbulent Prandtl numbers, and the gas constant may be set using the `GAS` keyword. Real gas chemistry models are selected using the `CHEMISTRY` keyword. Several different chemistry packages are available in the form of files containing thermodynamic data, finite rate coefficients, and transport property data, described in Section 7.9.

2.3.5 Numerical Model Controls

Time Stepping. In Wind-US, the number of iterations or time steps to perform in a given run is defined in terms of *cycles* and *iterations per cycle*. An iteration advances the solution one time step. A cycle consists of a solution pass over all the zones. Zone coupling, the process whereby Wind-US exchanges flowfield information between zones, only occurs at the end of each cycle. The Common Flow (*.cfl*) file is also updated only at the end of each cycle. The number of cycles to be performed is set using the `CYCLES` keyword, and the number of iterations per cycle, which may vary from zone to zone, is set using the `ITERATIONS` keyword. The default is five iterations per cycle.

The time step size is controlled by the `CFL#` keyword. By default, local time stepping is used, so that the solution advances at a different rate at each grid point. For unsteady problems, of course, the same time step size should be used throughout the flowfield, and an option is available with the `CFL#` keyword for this purpose. A Runge-Kutta time step formulation is also available, using the `STAGES` keyword, and may be used for both steady and unsteady flows.

See Section 4.1 for more information about cycles and iterations, and Section 4.5 for more about time step options.

[5] It should be noted that the algebraic models are older and infrequently used. They may not work as well as in some other codes, and there may be bugs in their implementation.

Implicit Operator. The IMPLICIT keyword allows a variety of implicit operators to be specified, including point Jacobi, Gauss-Seidel, and MacCormack modified approximate factorization. Also available are options to: (1) turn off the implicit operator completely, resulting in an explicit calculation; (2) use a scalar (diagonalized) implicit operator; or (3) use a full block implicit operator. For these last three options, a different implicit operator may be specified for each computational direction.

The default is to use the full block operator in viscous directions, and the scalar (diagonalized) operator in inviscid directions.

The IMPLICIT BOUNDARY keyword may be used to specify that implicit boundary conditions are to be used on "wall" boundaries. This should improve stability when the CFL number is above about 1.3.

Explicit Operator. Through use of the RHS keyword, a wide variety of explicit operators are available for evaluation of the first-derivative terms on the right-hand side. These include a central difference scheme, the upwind Coakley, Roe, Van Leer, and HLLE schemes, and modified versions of the Roe, Van Leer, and HLLE schemes for stretched grids. Depending on the type of scheme used, the accuracy may be specified as anywhere from first to fifth order. The default is Roe's second-order upwind-biased flux-difference splitting algorithm, modified for stretched grids.

Damping Schemes. Various smoothing options are available in Wind-US to dampen instabilities that may occur under certain conditions. These include second- and fourth-order explicit smoothing (SMOOTHING, BOUNDARY-DAMP), and total variation diminishing (TVD) flux limiting for some of the explicit operators (TVD, BOUNDARY TVD). More details on the various damping options are in Section 4.3.

Convergence Acceleration. The ACCELERATE keyword may be used, in conjunction with the SMOOTHING and CFL# keywords, to increase the time step near the beginning of a calculation, in order to more quickly get through the start-up transients that may occur in the first few hundred iterations.

A grid sequencing capability is also available, using the SEQUENCE keyword, that may help speed convergence. With this option, grid points are removed from selected regions of the flowfield, resulting in a coarse-grid solution which is obtained in a fraction of the time it would have taken for a full-grid solution. At the end of each run, the solution is interpolated back onto the original grid to aid in restarting the solution, and to provide a continuous flowfield for post-processing. The full grid should of course be used when the solution nears convergence.

See Section 4.6 for more information about the ACCELERATE option, and Section 4.2.1 for more about the grid sequencing capability.

Convergence Monitoring Parameters. The convergence criterion, in terms of the required value or reduction of the maximum residual, may be specified using the CONVERGE keyword. Integrated forces, moments, and/or mass flow may also be used to monitor convergence, by using the LOADS keyword to periodically compute and print these values for specified three-dimensional regions and/or two-dimensional areas of a computational surface.

For unsteady flow problems, where the time step is being specified in seconds and is the same throughout the flow field, a time history tracking capability is also available using the HISTORY keyword. Selected flow variables may be computed at specified grid points, and written to a separate *Time History* (*.cth*) file.

More information about monitoring convergence is presented in Section 2.5 of this tutorial, and in Section 6.

2.3.6 Test Case 4 Input

Boundary Condition Types. *GMAN* was used in graphical mode to set the boundary condition types and store the information in the *.cgd* file. The interface boundaries between the three zones were automatically identified, and the geometric interpolation factors were computed and stored in the *.cgd* file. The inflow boundary ($i = 1$ in zones 1 and 2) was labeled as "arbitrary inflow," the outflow boundary ($i = i_{max}$ in zone 3) was labeled as "outflow," and the top and bottom boundaries ($j = 1$ in zones 1 and 3, and $j = j_{max}$ in zones 2 and 3) were labeled as "inviscid wall."

The first step, obviously, is to start GMAN.

```
gman

                             ***** gman *****

          Select the desired version from the following list.

0) END
1) gman_pre optimized version

Enter number of executable.......[1]:

 ****************************************************************************
 * Warning: This software contains technical data whose export is           *
 * restricted by the Arms Export Control Act (Title 22, U.S.C., Sec 2751,   *
 * et seq.) or Executive Order 12470. Violation of these export-control     *
 * laws is subject to severe criminal penalties. Dissemination of this      *
 * software is controlled under DoD Directive 5230.25 and AFI 61-204.       *
 ****************************************************************************
            GMANPRE - Version 6.153 (last changed 2002/11/05 20:30:13)

                        Creating journal file 'gman.jou'.

  Enter SWITCH or GRAPHICS to change to graphics mode.

 GMAN:
```

At this point, you may enter commands individually at the `GMAN:` prompt. Or, you could enter `SWITCH` or `GRAPHICS` to enter graphics mode.

The rest of this section describes in detail the use of GMAN for the tutorial test case. The graphics mode steps are on the left, with the Main Menu steps left-aligned and the Menu Options indented. Most of these are accomplished in GMAN by clicking on the listed menu item using the left mouse button. A few require entering text in the prompt area at the bottom of the screen. (See the "Graphical User Interface Basics" section of the *GMAN User's Guide* for a description of the various sections of the GMAN screen layout.)

The command line equivalents are shown on the right. Note that, in general, several graphics mode steps become consolidated into a single command.

We first need to tell GMAN the name of the file containing the grid.

Graphics Mode	Command Line Mode
`Common File`	`file case4.cgd`
enter `case4.cgd`	

Next, we use GMAN's automated procedure to define zonal coupling information.

Graphics Mode	Command Line Mode
`BOUNDARY COND.`	`automatic couple face zone all`
`AUTO COUPLE`	
`RUN AUTO COUP`	

Next, for zone 1, we define the inflow and lower wall boundaries.

Graphics Mode	Command Line Mode
`PICK ZONE/BNDY`	`zone 1`
`1:` (*from Zone List*)	
`I1`	`boundary i1`
`MODIFY BNDY`	`arbitrary inflow`
`CHANGE ALL`	
`ARBITRARY INFLO`	
`BOUNDARY COND.`	`update`
`YES - UPDATE FILE`	
`PICK ZONE/BNDY`	
`J1`	`boundary j1`
`MODIFY BNDY`	`inviscid wall`
`CHANGE ALL`	
`INVISCID WALL`	
`BOUNDARY COND.`	`update`
`YES - UPDATE FILE`	

For zone 2, we define the inflow and upper wall boundaries.

```
Graphics Mode                     Command Line Mode

PICK ZONE/BNDY                    zone 2
   2:  (from Zone List)
   I1                             boundary i1
MODIFY BNDY                       arbitrary inflow
CHANGE ALL
   ARBITRARY INFLO
BOUNDARY COND.                    update
   YES - UPDATE FILE

PICK ZONE/BNDY
   JMAX                           boundary jmax
MODIFY BNDY                       inviscid wall
CHANGE ALL
   INVISCID WALL
BOUNDARY COND.                    update
   YES - UPDATE FILE
```

And for zone 3, we define the outflow and both wall boundaries.

```
Graphics Mode                     Command Line Mode

PICK ZONE/BNDY                    zone 3
   3:  (from Zone List)
   IMAX                           boundary imax
MODIFY BNDY                       outflow
CHANGE ALL
   OUTFLOW
BOUNDARY COND.                    update
   YES - UPDATE FILE

PICK ZONE/BNDY
   J1                             boundary j1
MODIFY BNDY                       inviscid wall
CHANGE ALL
   INVISCID WALL
BOUNDARY COND.                    update
   YES - UPDATE FILE
PICK ZONE/BNDY
   JMAX                           boundary jmax
MODIFY BNDY                       inviscid wall
CHANGE ALL
   INVISCID WALL
BOUNDARY COND.                    update
   YES - UPDATE FILE
```

Finally, it's a good idea to check the boundary conditions to make sure all is OK.

```
Graphics Mode                  Command Line Mode

TOP
CHECK                          zone all
CHECK BOUNDARY                 check boundary
   PICK ZONE
      ALL (from Zone List)
   RUN BNDY CHKS
```

After hitting the `Enter` key to return to GRAPHICS mode, we can quit GMAN.

```
Graphics Mode                  Command Line Mode

END                            exit
   YES - TERMINATE
```

Input Data (*.dat*) File. The Input Data File for Test Case 4, named *case4.dat*, is listed below. The explanatory notes, in italics, are not part of the file.

```
Wind-US test case 4, 2-D, 3 zones         Titles
Subsonic internal flow
Run 1

/ Inlet conditions
Freestream total 0.78 15.0 600.0 0. 0.    Inlet $M$, $p_t$ (psi), $T_t$ (°$R$), $\alpha$, $\beta$

/ Boundary conditions
Downstream pressure 14.13 zone 3          Exit $p$ (psi)

/ Numerics
Cycles 500                                Run 500 cycles
Iterations 5 Print frequency 5            5 iterations/cycle; print every 5th

/ Viscous terms
Turbulence euler                          Solve inviscid equations

/ Convergence data
Loads                                     Compute $\dot{m}$ every 5 iterations at:
   print planes frequency 5
   zone 1
      surface i 1 mass                        zone 1 entrance
   zone 2
      surface i 1 mass                        zone 2 entrance
   zone 3
      surface i 1    mass                     zone 3 entrance
      surface i last mass                     zone 3 exit
Endloads
```

2.4 Run the Code

2.4.1 The *wind* Script

Wind-US is invoked using a Unix script, called *wind*, which prompts for the executable to be used (since production and beta versions of Wind-US may both be available on a system), the names of the various input and output files (which should be entered *without* the three-letter suffix), and for the queue in which the job is to run. If a *multi-processing control* (*.mpc*) file is present with the same base name as the *.dat* file (see Section 2.4.2), it also issues a prompt to verify that the job is to be run in parallel mode. The script then links the files to the appropriate Fortran units, and either starts Wind-US interactively or submits the job to the specified "at" or "batch" queue. Details on the *wind* script are in Section 8.1.

There are a couple of very convenient features built into the *wind* script. The first allows a run to be stopped at (or more exactly, shortly after) a pre-determined time through the use of an *NDSTOP* file. This is useful when an overnight run must be stopped before morning, when the workstations being used will be needed for interactive work. The second allows the user to break a long run into "sub-runs," by writing a script called *wind_post* containing tasks to perform between each run. This is useful, for example, when the complete solution is to be saved at various time intervals in an unsteady problem. Details on the use of the *NDSTOP* file and the *wind_post* script are in Section 7.7 and Section 8.2, respectively.

2.4.2 Parallel Operation

When Wind-US is run in parallel mode, multiple systems connected via a network work together as though they were a single computer. These systems are typically workstation class machines and need not be all from the same vendor.

A master-worker approach is used. Grid zones are distributed from the master system to the worker systems for processing. (Note that the master may also be a worker.) Each zone is solved in parallel with other zones on other systems. The systems exchange boundary information at the end of each solution cycle to propagate information throughout the flowfield. If there are fewer workers than zones, a worker will be assigned another zone when it finishes its current assignment.

The user specifies the names of the participating worker systems via a *multi-processing control* (*.mpc*) file, which must have the same base name as the *.dat* file. The user must of course have accounts on the master and worker systems, and the master must be allowed to communicate with each worker, and vice versa, using remote shell commands, and without entering a password. (See Section 9.3.2.) This is all that is required to utilize the parallel processing capability of Wind-US. The PVM software needed for parallel operation, and Wind-US itself, will be copied from the master to temporary directories on the workers.

Additional details about running Wind-US in parallel mode may be found in Section 9.

2.4.3 Running Test Case 4

To run Test Case 4, simply issue the *wind* command, and respond to the prompts as appropriate. The following terminal session shows how the case was run as a serial batch job on a Unix workstation. Lines in slanted type were typed by the user.

```
% wind -runinplace
Running command line version of WIND.
```

```
                 ***** WIND Run Script *****


Current wind settings are:

--Wind test mode set to NODEBUG
--Wind debugger set to DEFAULT
--Wind run que set to PROMPT
--Wind run in place mode is set to YES
--Wind multi-processor mode set to NO
--Wind run directory set to PROMPT
--Wind bin directory set to /usr2/wind/wind

                 Select the desired version

  0: Exit wind
  1: Wind Version 3.0
  2: Wind Version 4.0
  3: Wind Version 5.0

Enter number or name of executable.......[3]:
Basic input data...............(*.dat): case4
Output data............(*.lis,<CR>=case4):
Mesh file..............(*.cgd,<CR>=case4):
Flow data file.........(*.cfl,<CR>=case4):

***********************************************************
case4.cfl does not exist, a fresh start will be performed.
***********************************************************


Enter a queue number from the following list or <CR> for default:
  1: REAL (interactive)
  2: AT_QUE
  3: QSUB_QUE
  4: QSUB_PBS_QUE

Queue name......................(<CR> for 1): 2


Enter at que (a,b..)................(<CR> for default):
Deferred start time..............(hhmm [day],<CR>=now):
Set stop flag at...........(hhmm [day],<CR>=don't set):

Version..............: /usr2/wind/wind/SGIMP6.5/R12000/wind5.exe
Input file name.......: case4.dat
Wind output to........: case4.lis
Grid file name........: case4.cgd
Flow file name........: case4.cfl
```

```
Job run que type is...: AT_QUE

Press <cr> to submit job, another key (except space) and <cr> to abort:
       warning: commands will be executed using /bin/sh
job 1090343885.b at Tue Jul 20 13:18:05 2004
All done, have a nice day!!
```

There are several points to note from this terminal session.

- This case was run using the *-runinplace* option to the *wind* script, which means that Wind-US will be run in the current directory, and that output files will be written in the current directory.

  The default is to run in a different (i.e., remote) directory, and is intended primarily for use with NFS-mounted home directories. In that case, it's faster to write the output files into a scratch directory on the system used to run Wind-US, rather than into the NFS-mounted home directory. The output files are automatically copied to the current directory at the end of the job.

  Note that the terminology here is unfortunately a bit confusing. With an NFS-mounted home directory, running remotely really means running on a system different from the one the home directory is on. The "remote" system may actually be the local system originally logged onto.

  If this case were run without the *-runinplace* option, the user would be prompted to enter the root name of the remote run directory, as follows:

  ```
  # Note the remote directory is assumed to exist on remote host #
  Enter the remote run root directory...(<CR> for /tmp):
  ```

  The full name of the remote run directory will be *rootname/userid/basename.scr*, where *rootname* is your response to the above prompt, *userid* is your userid, and *basename* is the base name of your *.dat* file. The default of */tmp* for the root name implies that, generally, the "remote" system is actually the one the user logged into. It also means that, if you aren't using NFS-mounted home directories, and you forget to add the *-runinplace* option, no real harm is done. The output will be created under */tmp*, then copied to the current directory when the job finishes.

- The default for the base name of the *.lis*, *.cgd*, and *.cfl* files is the same as that entered for the *.dat* file, and the three-letter suffixes *should not* be entered.

- A "fresh start" is being done for this case, since the *.cfl* file does not exist. If the *.cfl* file exists, Wind-US will automatically restart from the existing flow field.

- If the specified *.lis* file already exists, the output for the current run will be appended to the existing file. This typically occurs when restarting from a previous solution. If this isn't what you want, change the name of the existing *.lis* file before issuing the *wind* command.

- To run the job interactively, choose the `REAL` queue. This is intended mostly for debugging short runs, or checking that a case will successfully start. The user will be asked if the output should be written to the screen instead of the *.lis* file.

  The `AT_QUE` queue is used to run a batch job using the Unix *at* or *batch* command. If the response to the `Deferred start time` prompt is defaulted, the job will be started immediately using the *batch* command. Any other response will result in the *at* command being used to start the job at the specified time.[6]

[6] *Do not* type `now` in response to the prompt. That will result in an "at" job being submitted, and a "too late" error.

The QSUB queue choices shown above are intended for use on systems with NQS (Network Queueing System) software installed. The user will be prompted for the necessary NQS queue name, start time, etc. The QSUB choices will not appear on systems without a *qsub* command.

- As noted earlier, if a multi-processing control (*.mpc*) file is present, the user is also asked to verify that the job is to be run in parallel mode, as follows:

```
A multiprocessing control file exists....
Do you want to run in multi-processor mode (y/n,<CR>=y):
```

2.5 Monitor Convergence

For complex real-world applications, it is generally not feasible to expect a converged solution in a single run. The times required to achieve convergence are generally too long and problems may occur which could corrupt the solution. Thus, executing the code several times and restarting from the previous solution is often the best approach. If problems do occur, the input parameters can be adjusted without starting from scratch.

Monitoring and properly assessing convergence levels during a Wind-US run (as well as examining the flowfield itself, as discussed in Section 2.6) are thus crucial in obtaining meaningful, useful results. Wind-US users may track convergence by following residuals and/or integrated forces, moments, and mass flow via the LOADS keyword. For engineering applications, the recommended convergence monitoring method is the tracking of integrated quantities of interest. For example, if a wing/body geometry is being modeled to determine drag, the integrated drag should be monitored and some reasonable bounds on drag oscillations should be used as the convergence criterion.

The solution residuals are included in the *List Output* (*.lis*) file. For each zone, Wind-US prints the zone number, cycle number, location of the maximum residual, equation number for which the maximum residual occurred, the value of the maximum residual, and the L_2-norm of all the residuals for all the equations over all the points in the zone. By default, the residuals are printed each iteration. The output interval may be changed, however, using the CYCLES and ITERATIONS keywords.

The integrated parameters that are chosen in the Input Data file via the LOADS keyword will also be listed in the *.lis* file. The integration may be done over a number of specified three-dimensional regions and/or two-dimensional areas of a computational surface.

For unsteady flow problems, where a constant time step is being specified and is the same throughout the flow field, a time history tracking capability may be used. Computed values of selected variables at specified grid points may be periodically written to a separate *Time History* (*.cth*) file. This capability is activated using the HISTORY keyword.

A utility included with Wind-US called *resplt* can be used to extract the residuals and/or integrated quantities from the *.lis* file, and create a GENPLOT file[7] for post-processing.

An analogous utility called *thplt* can be used for the values stored in the *.cth* file.

Additional information about the various methods for monitoring convergence is presented in Section 6.

2.5.1 Test Case 4 Convergence

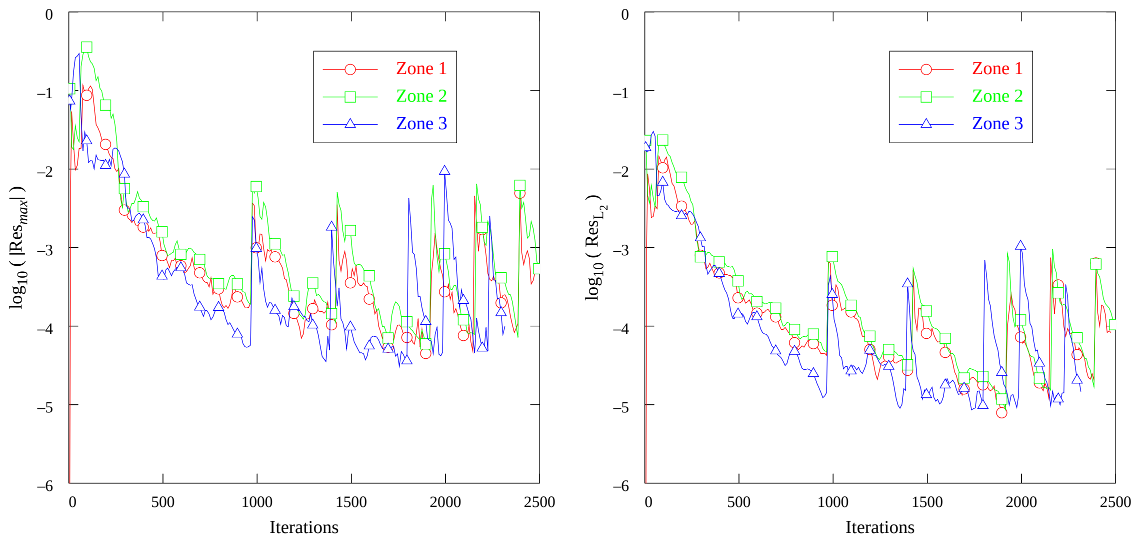
resplt was used to extract the maximum residual and the L_2-norm of the residuals from the List

[7] The format of a GENPLOT file is described in the *CFPOST User's Guide*.

Output (*.lis*) file and create GENPLOT files. As an example of the use of *resplt*, the following terminal session shows how a GENPLOT file containing the maximum residual was created. A GENPLOT file containing the L_2-norm of the residual was created similarly, using selection “2”. Lines in slanted type were typed by the user.

```
% resplt

                              ***** resplt *****

          Select the desired version from the following list.

0) END
1) resplt optimized version

Single program automatically selected.

 resplt - Version 1.8 (last changed 2004/04/09 14:44:52)
 ****************************************************************************
 * Warning: This software contains technical data whose export is           *
 * restricted by the Arms Export Control Act (Title 22, U.S.C., Sec 2751,   *
 * et seq.) or Executive Order 12470. Violation of these export-control     *
 * laws is subject to severe criminal penalties. Dissemination of this      *
 * software is controlled under DoD Directive 5230.25 and AFI 61-204.       *
 ****************************************************************************
  Enter full name of output list file:
case4.lis

Exit                  0
Select Zone(s)       91
Select Frequency     92
Select average mode  99
Confined Outflow
  Mass Flow Ratio    15
  Back Pressure      16
  Average p0         93
Residuals      Big   L2       Integ. Planes Zone Grand
  NS             1    2         Force     11     5    8
  k-e            3    4         Lift      17    18   19
  B-B           20   21         Moment    12     6    9
  S-A           22   23         Momentum  13     7   10
  SST           24   25         Mass      14    26    -
NEWTON NS       51   52         Heat Flx  54    55    -
Time History         53

Enter Selection
1
  Reading residual data...

  1466 data points read from list file.
  Sorting residual data...
  Sorting complete.

  Enter FULL name of genplot file:
chist.big.gen

Exit                 0
Select Zone(s)      91
Select Frequency    92
Select average mode 99
Confined Outflow
  Mass Flow Ratio   15
  Back Pressure     16
  Average p0        93
Residuals     Big   L2       Integ. Planes Zone Grand
  NS            1    2         Force     11     5    8
  k-e           3    4         Lift      17   18   19
  B-B          20   21         Moment    12     6    9
  S-A          22   23         Momentum  13     7   10
  SST          24   25         Mass      14   26    -
NEWTON NS      51   52         Heat Flx  54   55    -
Time History        53

Enter Selection
0
```

The convergence history for Test Case 4, in terms of the maximum residual and the L_2 norm of the residual, is shown in Figure 3.



(a) Maximum residual

(b) L_2 norm of the residual

Figure 3: Test case convergence history in terms of residuals

For this case, the residuals decrease about three orders of magnitude in the first 1000 or so iterations, then oscillate about a relatively constant value for the remainder of the iterations. This behavior is not at all uncommon. As noted above, it's usually more meaningful to use a physical quantity of interest when monitoring convergence. For this test case, one of the physical quantities of interest is the mass flow rate.

The Input Data file for this case specified that the integrated mass flux was to be computed at the entrances to all three zones, and at the exit of zone 3. GENPLOT files containing these integrated values were created using *resplt*, as illustrated above, using selection "14".

The time history for these parameters is shown in Figure 4, where the computed mass flux is plotted as a function of iteration number at the entrances to all three zones, and at the exit of the duct.

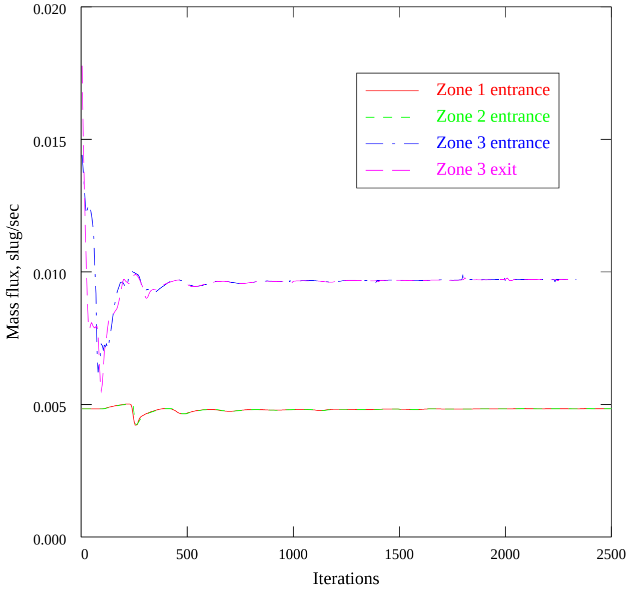


Figure 4: Test case convergence history in terms of mass flux

Based on the mass flux results, this case appears to converge within about 750–1000 iterations. Because this is a simple 2-D inviscid flow, with a coarse mesh, it converged quickly in a single run. The various convergence parameters were thus examined only at the end of the run. When running a more realistic, real-world configuration, convergence parameters like those shown in Figure 3 and Figure 4 should be examined at the end of each run. A more complete determination of convergence would also include examination of other physical quantities, such as the pressure distribution along the duct.

2.6 Examine the Results

Of course, the purpose of the solution process is to determine the features of the flow which can help answer the questions that drove the decision to perform the simulation in the first place. And, as indicated in the previous section, it's important to periodically examine the computed results during a run to help assess convergence and detect numerical problems that might be corrected by adjusting the input.

There are two types of information that can be extracted from the flow simulation — specific quantitative data and qualitative patterns. The first type includes things like pressure distributions, drag, and total flow rate. The second type includes, for example, 2-D slices or full 3-D visualization of pressure contours, streamlines, or isothermal surfaces.

2.6.1 Using CFPOST

All flowfield results computed by Wind-US, including the mean flow variables, turbulence model variables, and chemistry variables, are written into a Common File called a *Common Flow* (*.cfl*) file.[8] The CFPOST utility, included with the Wind-US distribution, is a post-processing tool for examining the contents of the *.cfl* file.

With CFPOST a wide variety of variables and integrated values may be computed. Listings of quantitative results may be sent to the screen or to a file. PLOT3D files may be created for other plotting packages and post-processors to use in displaying qualitative results. CFPOST can also be used to create x-y, contour, and vector plots directly, with PostScript output. Commands are available to precisely specify the information of interest, the domain of interest, and the units in which the results are to be presented. More details may be found in the *CFPOST User's Guide*.

2.6.2 Test Case 4 Results

The desired results from this calculation were the mass flow rate and the static pressure distribution. The mass flow rate is available in the List Output (*.lis*) file, as output generated via the `LOADS` keyword, and also from the GENPLOT files created while monitoring convergence. The result was 9.7×10^{-3} slug/sec.

To examine the static pressure distribution, CFPOST was first used to create a PLOT3D q file called *case4.q* from the Common Flow file *case4.cfl*, as follows:[9]

```
% cfpost

                              ***** cfpost *****

              Select the desired version from the following list.

0) END
1) cfpost_pre optimized version

Enter number of executable.......[1]:

           CFPOST - Version 3.163 (last changed 2002/11/05 20:28:28)
 ****************************************************************************
 * Warning: This software contains technical data whose export is           *
 * restricted by the Arms Export Control Act (Title 22, U.S.C., Sec 2751,   *
 * et seq.) or Executive Order 12470. Violation of these export-control     *
 * laws is subject to severe criminal penalties. Dissemination of this      *
 * software is controlled under DoD Directive 5230.25 and AFI 61-204.       *
```

[8] As noted previously, Wind-US also supports the use of CGNS files for the grid and flow solution, using the `CGNSBASE` keyword.

[9] CFPOST can also be used to create a PLOT3D xyz file, but as noted in Section 2.2.3, an xyz file for this configuration was created during the mesh generation process.

```
 ****************************************************************************
 CFPOST> solution case4.cfl
1Wind-US test case 4, 2-D, 3 zones
 Subsonic internal flow

 Freestream conditions (* indicates calculated)

 Mach number                   0.780
 Angle of attack               0.000 degrees
 Yaw angle                     0.000 degrees
 Gamma                         1.400
 Gas constant (R)            286.959 m2/s2-K         1716.000 ft2/s2-R
 Static pressure         69194.1     N/m2         10.0357     lbf/in2
 Static temperature      297.173     K            534.912     R
 Static density*        0.811408     kg/m3       0.157439E-02 slug/ft3
 Total pressure*         103421.     N/m2         15.0000     lbf/in2
 Total temperature*      333.333     K            600.000     R
 Total density*          1.08121     kg/m3       0.209790E-02 slug/ft3
 Speed of sound          345.524     m/s          1133.61     ft/s
 Velocity                269.509     m/s          884.216     ft/s
 Dynamic pressure        29468.4     N/m2         4.27402     lbf/in2
 Laminar Viscosity      0.183722E-04 kg/m-s      0.383710E-06 slug/ft-s
 Reynolds Number*       0.119029E+08 1/m         0.362800E+07 1/ft
 Enthalpy*               298468.     m2/s2       0.321268E+07 ft2/s2
 Stagnation Enthalpy*    334785.     m2/s2       0.360360E+07 ft2/s2
 CFPOST> subset i all j all k all
 CFPOST> zone 1
 CFPOST> zone 2
 CFPOST> zone 3
 CFPOST> plot3d q case4.q 2d mgrid unformatted
 Processing ZONE   1...
 Processing ZONE   2...
 Processing ZONE   3...
 CFPOST> quit
```

The PLOT3D xyz and q files were then used as input to other post-processing packages to examine the computed results. The computed static pressure distribution along the upper and lower walls is shown in Figure 5, and the static pressure field is shown in Figure 6.

2.7 Summary

The steps in the generalized solution process listed earlier may be expanded and restated specifically for Wind-US as follows:

- Gather information detailed enough to specify the problem within the required accuracy, including the geometry, flow conditions, and boundary conditions.
- Create a grid file using any convenient grid generation software, saving the file in PLOT3D xyz format.
- Convert the PLOT3D xyz file to a Common Grid (*.cgd*) file using *cfcnvt*.

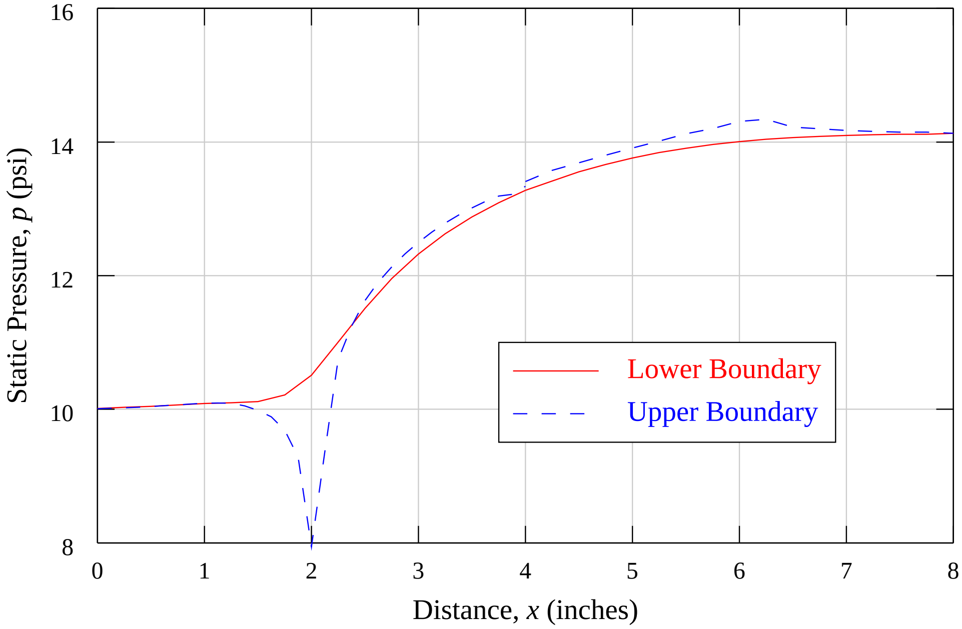


Figure 5: Test case static pressure distribution

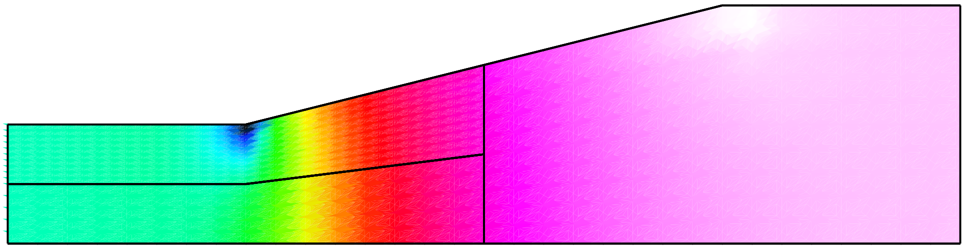


Figure 6: Test case static pressure field

- Store the boundary condition types and zonal connectivity data in the *.cgd* file using GMAN or MADCAP.
- Prepare the Input Data (*.dat*) file, defining boundary condition values, initial conditions, program control parameters, and integrated parameters for monitoring convergence.
- For parallel execution, prepare the *multi-processing control* (*.mpc*) file.
- Run Wind-US using the *wind* script supplied with the code.
- Monitor convergence by examining the residuals and integrated values in the List Output (*.lis*) file. The utilities *resplt* and CFPOST may be helpful.
- Periodically examine the computed results in the Common Flow (*.cfl*) file using CFPOST, creating PLOT3D files for other post-processing packages if desired.

3 Geometry and Flow Physics Modeling

3.1 Symmetry Considerations

Wind-US may be used with structured grids for axisymmetric, two-dimensional, or three-dimensional geometric configurations. Two-dimensional grids may be used not only for two-dimensional cases, but also for axisymmetric and area variation (quasi-three-dimensional) cases. Unstructured grids may be used only for three-dimensional configurations.

3.1.1 Three-Dimensional Cases

In three dimensions, each zone's computational mesh is comprised of six boundary faces and an interior grid. In structured grids, the mesh points are identified by three indices, usually labeled (i, j, k). In unstructured grids, each individual grid cell, and cell face, is numbered. Boundary conditions for each boundary face must be specified with GMAN or MADCAP before the grid may be used with Wind-US.

3.1.2 Two-Dimensional Cases

Two-dimensional cases may be run using structured grids only. The grid must be oriented such that the maximum k-index of the grid is one. In other words, a two-dimensional grid is defined by four boundary faces and an interior grid labeled by i- and j-indices. The grid must also reside in a non-zero, constant z-coordinate plane. The actual value used will not affect solution convergence or flowfield features, but it will affect flux-related post-processing calculations such as mass flow. For this reason, a value of 1.0 is recommended. Boundary conditions for the four boundary lines must be specified in GMAN or MADCAP.

3.1.3 Area Variation (Quasi-3D) Cases

With structured grids, the effect of area variation on two-dimensional computational models may be computed by using Wind-US's "quasi-three-dimensional" capability, which is activated simply through changes in the z-coordinate. The value of the z-coordinate is the "width" of the field at each grid point; the complete grid therefore represents the "width" variation of the field as a function of x and y. The important quantity to model is the ratio of cross-sectional areas between two adjacent axial stations. This means that the z-coordinate may be scaled with no effect on the computed flowfield, but a simple translation of the z-coordinates will change the computed flowfield, because the cross-sectional area ratio will be different. As with two-dimensional calculations, the value of the z-coordinate will affect flux-related post-processing calculations.

3.1.4 Axisymmetric Cases

Axisymmetric configurations may be modeled with structured grids, by using a two-dimensional grid generated at an arbitrary circumferential location on the geometry — e.g., the top centerline. Note that the grid should be generated on only one "side" of the configuration. Once again, the z-coordinate of the grid should be 1.0. The final step in using Wind-US's axisymmetric mode is the specification of the symmetry axis location and the circumferential sweep angle in the input data file. The circumferential sweep angle is the angle of the "pie shape" swept out by the grid about the symmetry axis. Although the value of the sweep angle will not affect the computed flowfield, it will affect flux-related post-processing calculations.

Keywords: `AXISYMMETRIC`

3.2 Euler and Navier-Stokes Equations

Wind-US may be used to solve the Euler equations or the Reynolds-averaged form of the Navier-Stokes equations (Bush, 1988). All heat transfer and stress tensor terms are retained, and the equations are modeled in full conservation form. The effects of turbulence may be modeled using a variety of algebraic, one-equation, and two-equation turbulence models. Modification of the effective heat transport coefficient due to turbulence is linked to the momentum diffusion coefficient by a turbulent Prandtl number, which is assumed to be constant.

The fluid may be treated as a thermally and calorically perfect gas, a thermally perfect gas, equilibrium air, or a mixture undergoing a finite rate chemical reaction. For an ideal gas, conventional values are given to the gas constant (R) and the ratio of specific heats (γ), or they may be specified. Effects of gravity (i.e., stratification) and rotation may also be included.

The equation set(s) to be solved must be specified in the input data file.

Keywords: `TURBULENCE`, `GRAVITY`, `ROTATE`

3.2.1 Freestream Conditions

Freestream flowfield conditions — Mach number, pressure, temperature, angle of attack, and angle of sideslip — must be specified in Wind-US's input data file. The Mach number must be greater than zero, and pressure and temperature may be specified as static or total values. These conditions are used to initialize the flowfield at the start of a run. For external flow problems, they are also applied at all inflow, outflow, and freestream boundaries during the course of a flow solution. For this reason, the outermost grid boundary should be far enough away from the body such that the freestream assumption is valid at the boundary.

Keywords: `FREESTREAM`

3.2.2 Reynolds Number Considerations

Wind-US does not allow the direct specification of a Reynolds number; freestream conditions must be specified that are consistent with the desired value. Currently, Wind-US uses a reference length which it computes based on the unit system of the grid file. The code prints out the reference length (in inches) that it uses, so that you may compare the Reynolds number from the code with the desired value. The Reynolds number in Wind-US's output is actually the Reynolds number "per reference length."

Here are a couple of examples.

Case I: Grid is same size as model

Suppose we have the grid for a wind tunnel model, and we want to run it at $M_\infty = 0.7$ and a Reynolds number of 12.1 million (based on the model length). We arbitrarily choose a total temperature of 520 °R (static temperature of 473.6 °R). Knowing the temperature, we can calculate the speed of sound ($a = \sqrt{\gamma RT}$) and viscosity (from Sutherland's law). Using the Mach number, we can calculate the freestream velocity. Thus, we have

$$\begin{aligned} M_\infty &= 0.7 \\ T_\infty &= 473.6\ ^\circ\mathrm{R} \\ U_\infty &= 746.67\ \mathrm{ft/sec} \\ \mu_\infty &= 3.474 \times 10^{-7}\ \mathrm{lb_f\text{-}sec/ft^2} \\ Re_L &= 12,100,000 \end{aligned}$$

We now have the Mach number and temperature for the Wind-US input data file, but we still need to calculate the freestream pressure. Using the definition of the Reynolds number (and the ideal gas law),

$$Re_L = \frac{\rho\, U\, L}{\mu} = \frac{P\, U\, L}{R\, T\, \mu}$$

or

$$P = \frac{R\, T\, \mu\, Re}{U\, L} = \frac{R\, T\, \mu\, Re_L}{U}$$

Note that Re_L is the Reynolds number per unit length of the physical model. For our example, if the model length is 10 inches,

$$\begin{aligned} Re_L &= 12,100,000/(10/12\ \mathrm{ft}) \\ &= 14,520,000(1/\mathrm{ft}) \end{aligned}$$

We can now calculate P:

$$\begin{aligned} P = \frac{R\, T\, \mu\, Re_L}{U} &= \frac{(1716)(473.6)(3.474 \times 10^{-7})(14.52 \times 10^6)}{746.67} \\ &= 5490.31\ \mathrm{lb_f/ft^2} = 38.13\ \mathrm{psi} \end{aligned}$$

We would now like to check our input. If we run Wind-US with the Mach, temperature and pressure specified above, the code will print a Reynolds number and a reference length near the top of the list output file. *To obtain the desired Reynolds number, divide Wind-US's value of the Reynolds number by the output reference length and multiply by the model body length. This number may be compared with the desired model Reynolds number.*

Case II: Grid is scaled from model size

Let us now assume that we want to run the previous grid at flight conditions, but we want to keep our same old 10-inch grid. We simply need to multiply the pressure by a scale factor. The equation now becomes:

$$P = \frac{R\, T\, \mu\, Re_L S}{U}$$

where

$$S = \frac{\text{Full Model Size}}{\text{Grid Model Size}}$$

For example, if we want to run a 100-inch wing using our 10-inch grid, $S = 10$. If we want to run a flight Reynolds number of 26 million, we calculate P as:

$$\begin{aligned} P &= \frac{(1716.5)(473.6)(3.47 \times 10^{-7})(26 \times 10^6)(10)}{746.67} \\ &= 983113.0\ \mathrm{lb_f/ft^2} = 682.72\ \mathrm{psi} \end{aligned}$$

3.2.3 Mass Flow in Two-Dimensional Calculations

One of the options available in Wind-US is the specification of mass flow boundary conditions for subsonic duct analyses. Actual or corrected mass flow may be specified at duct exits, as may back pressure.

Within Wind-US and many post-processors, routines exist which integrate mass flow at desired computational planes. For 3D cases, the desired mass flow may be compared directly with the output from the integration routines:

$$\dot{m} = \int \rho u \, dA$$

However, for 2D calculations, the comparison is not so straightforward. There are three cases to consider.

Case I: 2D, Unit Depth

The first case involves running Wind-US on a truly two-dimensional grid of *unit depth* (z-coordinate is 1.0 everywhere). In this case, the input mass flow should be *per unit depth.* For example, let's say we want to run a 2D, unit depth model of a duct with a square exit. (If the exit were not square, this model would probably not be very good.) We would like a corrected mass flow of 500 lb_m/sec, and our actual model exit depth is 10 inches. If the grid input units are inches, we should ask for a mass flow of 50 lb_m/sec. If the grid input units are *not* inches, simply divide the actual mass flow by the z-coordinate value *in inches.*

Case II: 2D, Variable Width

When the z-coordinate is the width of the 2D grid, Wind-US adds in the area variation as a source to the 2D equations, making the analysis quasi-three-dimensional. In this case, the actual 3D mass flow should be specified in the input file. The integrated exit area will be (approximately, see Section 3.2.4 the real duct exit area, if the width has been specified correctly.

Case III: 2D, Axisymmetric

Axisymmetric runs require specification of the symmetry axis location and the circumferential angle subtended by the 2D grid. (This angle has no influence on the solution, but it does determine the area perpendicular to the grid.) The only reason this angle is an input parameter is so that you will know what the streamwise area is. In this case, the real exit geometry is circular, with a corresponding mass flow. The ratio of the input mass flow to the actual mass flow should equal the ratio of the input circumferential angle to 360. For example, if we are modeling a circular duct with a mass flow of 200 lb_m/sec using an axisymmetric model in Wind-US, and if we specify a circumferential angle of 36 (1/10 of 360), we should specify a mass flow of 20 lb_m/sec (1/10 of 200 lb_m/sec).

3.2.4 Mass Flow and Grid Areas

When dealing with subsonic duct analyses, you should be aware that the duct area as represented by the grid may be slightly different from the real area of the geometry being modeled, especially for ducts modeled with quasi-polar structured grids.

The duct area represented by the computational grid is often smaller than the real duct area, which, when running near critical mass flow, may prematurely choke the flow in the CFD solution. If the duct is circular and is modeled with a quasi-polar grid, the area error may be estimated.

Suppose we are modeling a circular duct with a quasi-polar grid using $k_{max} = 33$ circumferential points, each of which lie on the perimeter of the real duct at some streamwise station. If the circumferential points are evenly distributed, we may describe this topology as a circle which circumscribes a regular polygon of $k_{max} - 1 = 32$ sides. For a circle of radius R circumscribing a regular polygon of n sides, the area of the polygon is

$$A_p = \frac{1}{2} n R^2 \sin \frac{360}{n}$$

which means that the "grid area" is

$$A_g = \frac{1}{2}(k_{max} - 1) R^2 \sin \frac{360}{k_{max} - 1}$$

For our example, with $k_{max} = 33$, the grid area is 0.7% lower than the actual area.

There is no need to worry about this difference for most cases, but you should be aware of its possible effects.

3.2.5 Heat Transfer

At solid walls, Wind-US uses an adiabatic heat transfer boundary condition by default. A constant wall temperature may also be specified in the input data file.

Through the use of the TTSPEC keyword, point-by-point wall temperature distributions may also be specifed on boundary surfaces in structured grids. An auxiliary code, *tmptrn*, is used to create the wall temperature distribution, and write it into the common flow (*.cfl*) file.

The thermal conductivity is determined using a constant Prandtl number.

Keywords: `WALL TEMPERATURE`, `TTSPEC`

3.2.6 Viscosity

By default, Wind-US uses Sutherland's law to define laminar viscosity as a function of temperature. Keye's formula may be used in addition to Sutherland's law, and Wilke's law may be used to compute the laminar viscosity for multi-species flows.

Keywords: `VISCOSITY`

3.3 Turbulence Models

For turbulent calculations, Reynolds averaging assumptions are used to define a turbulent (eddy) viscosity, which is added to the laminar viscosity in the flow calculations. All the turbulence models available in Wind-US are coupled to the Navier-Stokes equations only through the turbulent viscosity.

For structured grids, users have a choice of several algebraic, one-equation, and two-equation turbulence models. In addition, various combined RANS/LES models may be used. For unstructured grids, only one-equation models are currently available.

Note that a turbulence model (or inviscid or laminar flow) must be specified in the input data file. Wind-US will stop if you do not.

3.3.1 Algebraic Models

The algebraic turbulence models available in Wind-US for structured grids are the Cebeci-Smith model, the Baldwin-Lomax model (Baldwin and Lomax, 1978), and the P. D. Thomas model (Thomas, 1979), which adds a shear layer model to the Baldwin-Lomax model. After each iteration of the flow solver, these models compute the turbulent viscosity based on current flowfield quantities. Note that, because of their dependence on maxima and minima of flowfield variables, these models produce discontinuous turbulent viscosity distributions in the computed flowfield and require special numerical treatment at the juncture of two walls and on computational *i*-boundaries (the latter for historical reasons). The Baldwin-Lomax model is the most widely used algebraic turbulence model in Wind-US.

Keywords: `TURBULENCE`

3.3.2 One-Equation Models

Because of their efficiency and ability to produce continuous turbulent viscosity distributions, the one-equation turbulence models in Wind-US are the models of choice for many engineering applications. The one-equation models available in Wind-US for structured grids are the Baldwin-Barth (Baldwin and Barth, 1990) and Spalart-Allmaras (Spalart and Allmaras, 1992) models. The models available for unstructured grids are the Spalart-Allmaras and Goldberg pointwise models.

Keywords: `TURBULENCE`. `FREE_ANUT`

3.3.3 Two-Equation Models

Three two-equation turbulence models are currently available in Wind-US for structured grids — the Menter Shear Stress Transport (SST) model (Menter, 1993; Mani, Ladd, Cain, and Bush, 1997), the low-Reynolds-number Chien k-ϵ model (Chien, 1982), and the low-Reynolds-number Rumsey-Gatski k-ϵ algebraic Reynolds stress model (Rumsey, Gatski, and Morrison, 1999; Rumsey and Gatski, 2000; Yoder, 2003).

The Menter Shear Stress Transport (SST) model is a blend of k-ϵ and k-ω, and may be used with or without the compressibility corrections of Suzen and Hoffmann. The equations are cast in k-ω form. Near the boundary the k-ω model is used, and the k-ϵ model is used away from the wall and in shear layers. Freestream values of k and ω may be specified. Each equation is solved individually and an iterative method has been used on the left-hand side to reduce the factorization error. The model is robust, and may be more accurate in adverse pressure gradients than some of the other models in Wind-US.

The Chien k-ϵ model and the Rumsey-Gatski k-ϵ algebraic Reynolds stress model are also available in Wind-US. Several options may be specified with these models to control the initialization procedure, enhance stability, and improve accuracy in adverse pressure gradients and at high Mach numbers.

Keywords: `TURBULENCE`, `COMPRESSIBLE DISSIPATION`, `PRESSURE DILATATION`, `FREE_K`, `FREE_OM`, `K-E ...`

3.3.4 Combined RANS/LES Models

The idea behind combined RANS/LES (Reynolds-Averaged Navier Stokes / Large Eddy Simulation) turbulence models is to improve predictions of complex flows in a real-world engineering environment, by allowing the use of LES methods with grids typical of those used with traditional Reynolds Averaged Navier Stokes models. The combined model reduces to the standard RANS model in high mean shear regions (e.g., near viscous walls), where the grid is refined and has a large aspect ratio unsuitable for LES models. As the grid is traversed away from high mean shear regions, it typically becomes coarser and more isotropic, and the combined model smoothly transitions to an LES model.

Three different combined RANS/LES models are available in Wind-US for structured grids — the Spalart DES model, used in conjunction with the Spalart-Allmaras model (Spalart, Jou, Strelets, and Allmaras, 1997; Shur, Spalart, Strelets, and Travin, 1999), the SST model, with a limiter on ϵ, and the hybrid model of Nichols and Nelson, which may be used with both the SST and the Chien k-ϵ models (Nichols and Nelson, 2003).

The combined models may only be used for unsteady flows (i.e., the time step is a constant). They are zonal, however, so you can use a combined model in time-accurate mode in one zone, while using a standard RANS model in steady-state mode in the other zones.

Keywords: `TURBULENCE`, `DES`, `LESB`, `HYBRID`

3.3.5 Transition Specification

Through the use of the `TTSPEC` keyword, point-by-point transition data may be specifed on viscous walls in structured grids. The data represent the percentage of turbulent viscosity to be added to the laminar viscosity at each grid point. An auxiliary code, *tmptrn*, may be used to create the transition data, and write it into the common flow (*.cfl*) file.

Keywords: `TTSPEC`

3.4 Gas Models

A variety of gas models are available in Wind-US to complete the equation set. The fluid may be treated as a thermally and calorically perfect gas, a thermally perfect gas (frozen chemistry), equilibrium air, or a mixture undergoing a finite rate chemical reaction. Several different chemistry packages are available as files containing thermodynamic data, finite rate coefficients, and transport property data.

Keywords: `CHEMISTRY`

3.5 Other Models

For structured grids, various other models are available in Wind-US to model specific physical features of the geometry.

3.5.1 Actuator Disks

To simulate fan or compressor discontinuities, Wind-US provides an actuator disk modeling capability, which acts as a modification to the zone coupling boundary condition. The model assumes an infinitesimally thin disk and must be applied at a coupled zonal interface. The actual discontinuity is specified in the input data file as a solid-body rotation or free vortex flow, the effects of which are applied when transferring flow information between the two specified zone boundaries.

Keywords: ACTUATOR

3.5.2 Screens

Flowfield screens may also be modeled in Wind-US as discontinuities across coupled zonal interfaces. In the Wind-US input data file, one must specify the zones and boundaries between which the screen in located, the solidity of the screen, and one of several methods for calculating the losses through the screen. The screen model is not intended for use with choked screens, where the screen is significantly limiting the mass flow rate. During the solution start-up phase, it may be necessary to specify a low solidity, then increase it to the desired value to avoid strong choking in transients.

Keywords: SCREEN

3.5.3 Vortex Generators

A model is available in Wind-US for the effects of an array of vane-type vortex generators in three-dimensional flow. Currently, the generators must be located at a coupled i-interface boundary between two zones. A discontinuous change in secondary velocity is applied across the interface to simulate the vortices produced by the generators.

The model is based on experimental data, and determines the strength of each vortex based on the generator chord length, height, and angle of incidence with the incoming flow, as well as the incoming flow core velocity and boundary layer thickness. Each vortex center is placed at the grid point closest to the location determined by the user-specified generator location on the boundary, and the generator height.

Keywords: VORTEX GENERATOR

3.6 Flowfield Initialization

By default, Wind-US initializes the computational flowfield by setting the flow properties at each grid point equal to those specified with the FREESTREAM keyword in the input data file. The same initial conditions are applied at all points in the computational domain, including solid walls, zone boundaries, and freestream boundaries.

Several options in Wind-US lead to non-default initializations, including user-specified inflow conditions, boundary layer initialization, and reinitialization of portions of the flowfield on restart. The user-specified inflow and boundary layer initialization options are currently only available for structured grids.

3.6.1 User-Specified Initialization

Wind-US's ARBITRARY INFLOW keyword was designed to specify flow conditions at arbitrary inflow boundaries.[10] However, it may also be used in a variety of ways to specify initial conditions in selected portions of the computational domain that are different from the freestream values. This capability may be useful, for example, when modeling a jet emanating from a solid wall. Zones downstream of the jet exit may have difficulty converging to the proper solution from conditions much different than the jet exit conditions.

To use the ARBITRARY INFLOW keyword as an initialization tool, specify the appropriate parameters and values for a zone as described below, and run Wind-US from scratch (i.e., without an existing flow (*.cfl*) file).[11]

There are three ways that the ARBITRARY INFLOW keyword may be used to modify the default initial conditions.

- If uniform inflow is specified for a particular zone using the UNIFORM parameter, the flow *throughout that zone* will be initialized to the conditions specified.
- The IJK_RANGE parameter may be used to set flow conditions over an arbitrary range of i, j, and k indices in any computational region. Up to 500 IJK_RANGE parameters are allowed. The default initial conditions will be used at points outside the specified range(s).
- The USERSPEC parameter may be used to specify a 1-D profile normal to the surface, translated through some buttline range, below the vehicle. Note that this option only applies to points in the $i = 1$ computational plane. The default initial conditions will be used at the remaining points.

Keywords: ARBITRARY INFLOW

3.6.2 Boundary Layer Initialization

To provide a better approximation to near-wall flowfields, Wind-US provides a couple of boundary layer initialization options that may help speed the convergence of viscous flows near solid walls.

First, by using multiple IJK_RANGE parameters with the ARBITRARY INFLOW keyword, and setting the range to include not only the inflow boundary but also locations downstream, one can set initial boundary layer profiles all along the viscous walls. Note that using this capability may add many lines to the input data (*.dat*) file. The INCLUDE keyword may be useful in keeping the main *.dat* file to a manageable size.

Another option is to use the BL_INIT keyword to specify a starting location and thickness for a laminar or turbulent boundary layer. However, this option may only be used on computational j- or k-boundaries, and only on one boundary in each zone.

Keywords: ARBITRARY INFLOW, BL_INIT

[10] Recall that the type of boundary, such as arbitrary inflow, is specified using GMAN or MADCAP, and stored in the common grid (*.cgd*) file, not in the input data file.

[11] Note that since the ARBITRARY INFLOW keyword is also used to specify boundary conditions at arbitrary inflow boundaries, a conflict arises if (for some reason) the desired inflow properties are different from those being set as initial conditions. In this case, the ARBITRARY INFLOW keyword can still be used to set initial conditions by setting the number of cycles to be run to zero. Then, after changing the values specified with the ARBITRARY INFLOW keyword to the desired inflow values, simply restart using the initialized flowfield in the newly-created *.cfl* file.

3.6.3 Reinitialization

In the event that portions of the computed flowfield become "polluted" with unrealistic flowfield data, due to numerical instabilities or other causes, you may wish to reinitialize portions of the flow. Wind-US's reinitialization option enables you to reset the flow conditions in specified zones.

For both structured and unstructured grids, conditions throughout the zone may be reinitialized to freestream values. In addition, for structured zones, conditions at all or specified grid points may be reinitialized to freestream values, or to values specified using the `ARBITRARY INFLOW` keyword and/or the `BL_INIT` keyword, as described above.

Keywords: `REINITIALIZE`, `ARBITRARY INFLOW`, `BL_INIT`

4 Numerical Modeling

Wind-US utilizes a number of different numerical methods in the solution of a selected set of field equations.

4.1 Iterations and Cycles

The usual method of obtaining a solution with Wind-US involves the initialization of the entire flowfield and the successive iteration of the flow solver, with appropriate boundary conditions, to a steady-state solution. Most boundary conditions are updated after each iteration of the flow solver; however, because of its expense, zone coupling takes place less frequently. Zone coupling is the process whereby Wind-US exchanges flowfield information between zones to maintain solution continuity at zonal interfaces. Updates of the flow file with the most current data also take place less frequently.

To facilitate flow file (see Section 7.3) updates and propagation of flowfield information to neighboring zones, Wind-US defines a “cycle” as a specific number of iterations performed in each of the zones, with zone coupling to effect information transfer. By default, Wind-US performs five iterations in each zone before moving on to the next zone. You must specify the number of solution cycles to be computed, and you may optionally specify the number of iterations per cycle to be calculated in each zone (or all zones simultaneously).

For single-zone problems, you may wish to specify a large number of iterations per cycle, because there is no need for zone coupling operations; however, note that the flow file will be updated less frequently in this case. For multi-zone problems, a large number of iterations per cycle is not recommended, because it will greatly hinder the transfer of flowfield information between zones and, therefore, convergence.

4.1.1 “Turning Off” Zones

To “turn off” a zone in a multi-zone calculation, simply specify 0 or fewer iterations per cycle for that zone; values of -1 and -2 are used to indicate how zone coupling is to be handled for zones adjacent to the “dead” zone.

Keywords: `CYCLES`, `ITERATIONS`

4.2 Grid Considerations

Wind-US provides capabilities which allow you to make the most efficient use of the computational grid for a given configuration. The options described in this section will significantly reduce the CPU time required. However, the accuracy of the computations in one or more grid directions is also reduced, and they should therefore not be used haphazardly.

These options are only available for structured grids.

4.2.1 Grid Sequencing

Grid sequencing is a capability whereby Wind-US “removes” grid points from selected portions of the domain, resulting in a “coarse grid” solution which is obtained in a fraction of the time it would have taken for a "full grid" solution. For example, if you select one level of sequencing in all three directions in a particular zone, only every other grid point in each of the i-, j-, and k-directions will be used in the calculations, resulting in a decrease in CPU time of approximately 80–90%. (The speed-up is not a linear function of the number of sequencing levels.) Selecting two levels of sequencing would repeat the process, causing only every fourth grid point to be used. At the end of each run, the solution is interpolated back onto the entire grid to aid in restarting the solution and to provide a continuous field for post-processing.

Grid sequencing is very useful for converging gross flowfield properties before obtaining a final solution on the full grid. Note, however, that a sequenced solution may seem incorrect when post-processed using the entire computational grid, because of the interpolation process used at the end of each run. In addition, when restarting a full-grid solution from a sequenced solution, reducing the CFL number (time step) by 50% is highly recommended, in order to reduce the risk of solution instabilities which arise during the transition.

Keywords: `CFL#`, `SEQUENCE`

4.2.2 Thin-Shear-Layer Calculations

Another time-saving option available in Wind-US is the ability to solve the thin-shear-layer Navier-Stokes equations, instead of the full equations. By requesting that Wind-US remove the viscous terms from the equations in one or more computational directions, a CPU savings of up to 30% may be realized. This capability requires careful specification, because viscous terms must be retained along grid lines which are perpendicular to boundary layers, free shear layers, and other highly viscous flow features.

Because some solution instabilities have been linked to the use of the thin-shear-layer option, it is recommended that you disable this option near the completion (convergence) of your solution, creating a fully viscous flowfield model.

Keywords: `TSL`

4.3 Explicit Operator

The first-derivative (non-viscous) terms on the right-hand side of Wind-US's equation set are calculated by the code's explicit operator. You may choose from a wide variety of explicit operators, independently of the implicit (left-hand-side) operator. An explicit operator is selected by its type and accuracy.

For structured grids, the explicit operators available include a central difference operator, the upwind Coakley, Roe, Van Leer, HLLE, and Rusanov schemes, plus modified versions of the Roe, Van Leer, HLLE, and Rusanov schemes for stretched grids. Depending on the type of scheme used, the accuracy may be specified as anywhere from first to fifth order. The default is Roe's second-order upwind-biased flux-difference splitting algorithm, modified for stretched grids.

For unstructured grids, only the cell-centered HLLE, Roe, and Rusanov operators are available. The accuracy may be first or second order.

Keywords: `RHS`

4.3.1 Explicit Smoothing

Certain types of explicit operators — for example, the central difference operator for structured grids — may require the addition of numerical smoothing in order to dampen instabilities which are a natural part of the scheme. Smoothing must also be added explicitly when utilizing Wind-US's convergence acceleration capability. Values for various smoothing parameters may be specified in the input data file for both structured and unstructured grids.

Keywords: `ACCELERATE`, `SMOOTHING`

4.3.2 Explicit Boundary Damping

In flowfields dominated by acoustic phenomena, unwanted wave reflections may sometimes occur at freestream computational boundaries. To eliminate these unphysical reflections, Wind-US's boundary damping capability may be employed with structured grids to apply explicit smoothing near the freestream boundaries, with the effect of absorbing the reflected waves.

Keywords: `BOUNDARY-DAMP`

4.3.3 Total-Variation-Diminishing (TVD) Operator

Certain types of explicit operators are equipped with a Total-Variation-Diminishing (TVD) operator, which limits local maxima and minima in flux quantities to prevent non-physical instabilities from arising during the solution. The default Roe scheme, for example, requires interpolation and/or extrapolation of flux quantities, which may produce minima or maxima that are outside the range of the original data. TVD operators attempt to limit these peaks to acceptable values based on the data used in the interpolation and extrapolation.

Three different TVD operators are available in Wind-US, for structured grids only, and may be specified on a zonal basis. For two of the operators, the severity of the limiting may be controlled through an input parameter.

Because only single data points are used in the first-order schemes, TVD, which limits interpolations and extrapolations, has no effect on such cases. It will only have an effect for second- and higher-order calculations. When attempting to model precise phenomena, such as acoustic waves, TVD should *not* be used, because it may produce undesirable damping or smearing of flowfield features. However, in most cases, TVD provides significant protection against numerical instabilities with less than a 10% increase in CPU time.

Keywords: `TVD`, `BOUNDARY TVD`

4.4 Implicit Operator

The left-hand side of Wind-US's equation set is computed in the code's implicit operator, which may be set on a zonal basis.

For structured grids, options are available to select scalar or full block implicit operators, or to turn off the implicit operator completely for an entirely explicit calculation. With these options, a different implicit operator may be specified for each computational direction. By default, Wind-US uses the full block operator in viscous directions, and the scalar (diagonalized) matrix solver in inviscid directions.

A variety of other implicit operators are also available for structured grids, including point Jacobi, Gauss-Seidel, MacCormack's modified approximate factorization, and the ARC3D 3-factor diagonal scheme as used in the OVERFLOW code.

For unstructured grids, a point Gauss-Seidel operator is used, and the equations may be solved as either a full block or diagonal matrix system.

Keywords: IMPLICIT

4.4.1 Implicit Boundaries

In addition to the normal explicit boundary conditions, implicit boundary conditions may be used on "wall" boundaries in structured grids. These improve stability when the CFL number is above about 1.3.

Keywords: IMPLICIT BOUNDARY

4.5 Time Step

The time step can be one of the most important parameters in a Wind-US solution. It may mean the difference between a successful run and a code bomb. For steady flow problems, the time step is represented by the CFL (Courant-Friedrichs-Lewy) number, which is a non-dimensional time step based on the actual time step, the local grid spacing, and the local characteristic velocity $(u + c)$. For unsteady flow problems, the time step in seconds must be specified directly.

4.5.1 CFL Number, Structured Grids

For stability reasons, the default CFL number is 1.3, which is sufficient for a wide variety of problems using structured grids. For inviscid solutions, the value may be raised slightly, while for highly complex flows (due to complex geometry or gas models), it may need to be lowered significantly. Often, in the beginning of a solution, or during the transition between a sequenced and fine grid solution, the CFL number should be set to 0.5 while transients settle out of the flowfield.

If you must consistently set the CFL number to 0.1 or lower to maintain stability in the solution, you should attempt to locate other possible causes of numerical instability, such as grid anomalies or grid/flow interactions. Such low CFL numbers translate into small time steps and unacceptable convergence rates.

When a CFL number above 1.3 is desired, the implicit boundary conditions should be used.

By default, Wind-US computes the time step from the input CFL number by using the minimum time step associated with the eigenvalues of each coordinate direction individually. That is:

$$dt = \min\left(\frac{\text{CFL}}{\lambda_x}, \frac{\text{CFL}}{\lambda_y}, \frac{\text{CFL}}{\lambda_z}\right)$$

Using TEST 105, the user may define the time step in various other ways, including the more conventional formula

$$dt = \frac{\text{CFL}}{\lambda_x + \lambda_y + \lambda_z}$$

which provides a somewhat smaller effective time step.

Options in Wind-US allow the CFL number or time step to be gradually increased as the calculation proceeds, or to use the time step calculation procedure from the OVERFLOW CFD code.

For most calculations, the time step is computed based on a constant CFL throughout the field, which means that, for non-uniform grids, a local time step is used, and the solution advances at different rates in different parts of the grid. Because the CFL number is directly proportional to the physical time step and inversely proportional to the local grid spacing, the physical time step must be small where the grid spacing is small, in order to maintain a constant CFL number. For example, in boundary layers and shear layers, where the grid is often closely packed for better resolution, the solution advances more slowly than in other parts of the flowfield. In fact, most of the iterations in a viscous solution are spent converging viscous regions. In practice, the major flow features (e.g., shocks and other major pressure gradients) will develop quickly, while detailed flow phenomena will require a larger number of iterations.

Wind-US therefore uses by default a “cross-flow” CFL number which multiplies each coordinate direction’s eigenvalues by a factor before determining the time step associated with that spacing and flow conditions. This factor varies from 1.0 when the flow is along the coordinate direction, to a user-specified value when the flow is perpendicular to the coordinate direction. The far-field CFL number is generally the value specified in the input data file with the `CFL#` keyword, but near the wall the code effectively uses a larger value. This should increase convergence of the boundary layer.

The cross-flow CFL factor is defined using the `CROSSFLOW` keyword. Values greater than one effectively increase the time step in the boundary layer (where the flow is parallel to the wall, but the minimum spacing is normal to the wall) by the specified factor. The default is 2.0 for three-dimensional flow, and 1.0 (i.e., no time step increase in the boundary layer) for two-dimensional flow and axisymmetric flow.

Keywords: `CFL#`, `CROSSFLOW`

4.5.2 CFL Number, Unstructured Grids

With unstructured grids in Wind-US, a much larger CFL number is normally used than the default value of 1.3. A reasonable starting value is 10, and values as high as 50 may be used as the calculation proceeds.

Wind-US computes a local time step for each cell from the input CFL number by using the minimum time step associated with the eigenvalues at each face of the cell. That is:

$$dt = \min\left(\frac{\mathrm{CFL}}{\lambda_{f1}}, \frac{\mathrm{CFL}}{\lambda_{f2}}, \cdots\right)$$

Options in Wind-US allow the CFL number to be gradually increased as the calculation proceeds.

4.5.3 Runge-Kutta Time Step

For structured grids, several Runge-Kutta time step formulations are available for use in Wind-US. A traditional four-stage Jameson-type scheme or a three-stage, minimal-storage scheme may be selected in the input data file. You may also specify algorithm coefficients for each of the stages in the different schemes.

Runge-Kutta schemes attempt to provide a more accurate approximation to the solution at the next time level by advancing through several stages, or sub-iterations, to get there. In Wind-US, each sub-iteration may be one pass through the explicit operator with or without a pass through the implicit operator. (The original Runge-Kutta scheme was formulated using only an explicit operator.) Depending on the coefficients used, Runge-Kutta time step algorithms are often higher order in time than the default Euler time stepping algorithm. This makes them ideally suited for time-accurate calculations (see below).

Keywords: STAGES

4.5.4 Time-Accurate Solutions

The objective of time-accurate CFD calculations is the modeling of unsteady flow phenomena, such as vortex pairing or bluff body wakes. In unsteady calculations, a global physical time step must be used throughout the entire flowfield, regardless of the local grid distribution. Because the CFL number has a limit which approximates the upper limit of numerical stability, the global time step must be obtained from the maximum CFL number and the smallest grid spacing in the field. Thus, the stability of the calculations in regions of dense grid packing determines the time step for the entire flowfield.

For structured grids, the options specified with the CFL# keyword determine whether the input value is interpreted as a CFL number, or a physical time step. For single-zone time-accurate calculations, an option is also available to set a global time step, equal to the minimum time step in the zone based on the specified CFL number. However, for multi-zone time-accurate calculations, you must calculate the time step yourself, based on the desired CFL number and the minimum grid spacing, and specify the physical time step in the input data file.

For unsteady flows with structured grids, the use of second-order time marching is recommended, possibly in combination with Global Newton iteration.

For unstructured grids, the time step is specified using the CFL# keyword, and the separate TIMEMARCHING keyword is used to indicate that the input value is to be interpreted as a global physical time step, and not a CFL number.

Keywords: CFL#, IMPLICIT ORDER, NEWTON, TIMEMARCHING

4.5.5 Global Newton Iteration

For structured grids, a Global Newton iteration technique is available in Wind-US, and has proven to provide time-accurate solutions with large CFL numbers for unsteady flows with large time scales (Tramel and Nichols, 1997). The Global Newton technique stabilizes the solution and improves time accuracy by placing the entire unsteady transport equations on the right-hand side of the matrix solver, and iterating within a time step over all the zones. Thus, the interface boundaries are brought up to the new time level, along with the interior flow field, resulting in an essentially implicit treatment of the boundaries. The Global Newton algorithm has also been shown to improve steady-state convergence rates (Nichols and Tramel, 1997).

Keywords: NEWTON

4.6 Convergence Acceleration

The solution transients that occur in iterating from the freestream-initialized flowfield often cause the most severe stability problems in Wind-US. As the solution approaches convergence on a sequenced grid, most of these transients will have settled out of the field, with the change to fine grid being the only remaining "jolt" to the solution. Numerical stability may be forced through the addition of artificial numerical dissipation to the equations, but such dissipation may lead to non-physical results in the steady state solution.

The convergence acceleration capability in Wind-US allows the use of a large CFL number at the start of a calculation, with artificial dissipation used to eliminate stability problems, to get past the starting transients more quickly. The CFL number and the dissipation are then lowered as the calculation proceeds.

For structured grids, you may specify the starting and ending values of the CFL number, the initial amount of artificial dissipation (smoothing) to be added to the equations, the iteration numbers between which the smoothing should be applied and CFL number altered, and the zone(s) in which you would like to enable this capability. At the beginning of the solution, a relatively high CFL number will be accompanied by significant numerical smoothing. As the iteration count approaches the specified ending value, the CFL number will be gradually adjusted toward its final value as the amount of smoothing is steadily decreased. Details, as well as recommended values for the smoothing coefficients, are presented with the `ACCELERATE` keyword description (see p. 99).

For unstructured grids, only the CFL number variation and the zone are specified with the `ACCELERATE` keyword. No variation in smoothing is done; the same amount of smoothing is used for all iterations, as specified using the `SMOOTHING` keyword. To reduce the amount of smoothing after the initial stages of the calculation, you must restart the solution with less dissipative smoothing values.

Keywords: `ACCELERATE`, `SMOOTHING`, `TEST 49 2`

5 Boundary Conditions

The boundary conditions are perhaps the most important factor in influencing the accuracy of the flow computation. The manner in which the boundary conditions are imposed also influences the convergence properties of the solution. Wind-US uses a cell-vertex discretization, which results in solution points located on the boundaries of the zones which comprise the flow domain. During the computation, Wind-US computes the boundary values for the conservative variables, the species (if present), and turbulence variables (if present).

Proper specification of the flow boundary conditions is aided by a basic understanding of characteristic theory of the incoming and outgoing waves normal to the boundary. The boundary normal is considered positive when it points into the flow domain. The wave speeds (eigenvalues) have convective and acoustic components. A positive wave speed indicates a wave entering the flow domain, and so, a physical boundary condition must be specified and some auxiliary information must be supplied to impose the boundary condition. A negative eigenvalue indicates a wave leaving the flow domain, and so, a numerical boundary condition can be specified using flow data within the domain. The waves moving tangential to the boundary are neglected in the boundary condition treatment.

5.1 Explicit and Implicit Boundary Conditions

Wind-US imposes the boundary conditions explicitly after the interior solution has been computed for each zone after each iteration, by default. An exception is the zone interface boundaries, which are updated after each cycle. Another exception is the mass flow boundary condition, which is updated after a specified number of iterations (the default is five iterations) in order to reduce computational effort. Errors due to explicit boundary conditions are reduced through the use of the multi-stage or iterative time integration methods.

The use of implicit boundary conditions with an implicit solver is known to improve the stability of the method and lead to faster convergence at the expense of greater computational effort and complexity. Implicit boundary conditions are available in Wind-US in a limited manner, primarily for wall boundary conditions. The `IMPLICIT BOUNDARY` keyword is used to turn on implicit boundary conditions.

Keywords: `IMPLICIT BOUNDARY`

5.2 Boundary Condition Types

The Grid MANipulation (GMAN) program is used to associate boundary condition types with the solution points on the boundaries of the zones. These boundaries represent the geometry model, fluid boundaries, grid topological boundaries, and couplings between zones. The type of boundary conditions available in GMAN, in the order displayed by GMAN, include[12]:

- `undefined`
- `reflection`
- `freestream`
- `viscous wall`
- `arbitrary inflow`

[12] In this User's Guide, GMAN boundary condition types are indicated by lower-case words in a fixed-pitch font, `like this`; Wind-US keywords are displayed in an upper-case fixed-pitch font, `LIKE THIS`.

- outflow
- inviscid wall
- self-closing
- singular axis
- coupled
- bleed
- pinwheel axis
- frozen
- chimera

It is possible to group some of these boundary condition types in a logical manner for detailed discussions, which are presented below. Some boundary conditions require further information, which is provided through keywords in the input data file, beyond being flagged in GMAN.

5.3 Wall Boundary Conditions

The inviscid wall, viscous wall, and bleed boundary condition types are all wall boundary conditions which simulate interaction of the flow with a real or imaginary solid surface.

5.3.1 Inviscid Wall

The inviscid wall boundary condition imposes flow tangency at the zone boundary (wall surface) while maintaining the same total velocity as the point adjacent to the boundary. One numerical boundary condition is imposed by computing the pressure at the boundary through an interpolation of interior pressures. A zero-order extrapolation is robust; however, the pressures may not be smoothly varying at the boundary. A first-order extrapolation works well for flows without discontinuity, and for flows in which the pressure does not vary greatly normal to the boundary. The extrapolations across a discontinuity may result in nonphysical pressures. One can use the viscous wall boundary condition along with the TURBULENCE INVISCID keyword in the input data file. This is useful if one wants to start a computation with the boundary as inviscid and then later turn on the viscous boundary conditions. In Wind-US, it is also possible to specify through TEST 138 that the normal pressure gradient at the wall be calculated rather than simply assuming it to be zero. Also, a first-order extrapolation which accounts for grid spacing can be used through the use of TEST 141.

5.3.2 Viscous Wall

The viscous wall boundary condition imposes a no-slip condition of the flow, a zero pressure gradient, and the appropriate heat transfer condition (adiabatic or constant temperature) at the zone boundary (wall surface). The no-slip condition can involve a non-zero velocity if the wall is moving. (See the MOVING WALL and ROLL keywords; however, for moving walls, the boundary condition type should be set to bleed.) To minimize transients at the start of a Wind-US calculation, the velocity at no-slip boundaries is actually reduced from its initial value to the no-slip condition over a number of iterations. The number of iterations may be specified using the WALL SLIP keyword.

The choice of the heat transfer condition is determined through the use of the WALL TEMPERATURE keyword in the input data file. The default is an adiabatic wall (zero temperature gradient). The temperature for the constant temperature condition is specified through the WALL TEMPERATURE keyword. The TTSPEC keyword is available for specifying a point-by-point distribution of surface temperatures.

Wall function boundary conditions may be used at viscous walls, using the White-Christoph law of the wall, through the WALL FUNCTION keyword. This feature is currently available for single-species flows only.

In Wind-US, it is also possible to specify through TEST 138 that the normal pressure gradient at the wall be calculated rather than simply assuming it to be zero. Also, a first-order extrapolation which accounts for grid spacing can be used through the use of TEST 141. Viscous flow is computed when the TURBULENCE keyword is used.

Keywords: MOVING WALL, TTSPEC, TURBULENCE, WALL FUNCTION, WALL SLIP, WALL TEMPERATURE

5.3.3 Bleed

The bleed boundary condition allows mass to flow through a porous, viscous wall. Bleed is mass flow out of the flow domain, while blowing is mass flow into the flow domain. Bleed and blowing systems are often an integral part of aeropropulsion configuration design, helping to control such flow phenomena as boundary layer growth and mixing. Wind-US's bleed / blowing boundary condition was designed to provide a means to model these systems with CFD. Specification of the bleed boundary condition in GMAN, which involves the identification of a particular bleed region number, triggers the calculation of the area of the bleed region specified, which is then stored in the grid file. Wind-US uses this area and the bleed or blowing conditions specified in the input data file to compute a normal velocity on the model surface. Bleed may be specified as a mass flow, or as a porous surface with a discharge coefficient and back pressure. Blowing may be specified through mass flow, plenum, or valve conditions.

Keywords: BLEED, BLOW

Moving Wall. The moving wall boundary condition enables a tangential velocity to be applied at no-slip walls in order to model rotating hubs or other components in the flow. The boundary solution points for the moving wall should be identified as bleed regions in GMAN. The translating or spinning motion of the wall is specified through the MOVING WALL keyword in the input data file. The ROLL keyword allows a rolling motion to be imposed on the grid.

Keywords: MOVING WALL, ROLL

5.4 Flow Interface Boundary Conditions

The freestream, arbitrary inflow, and outflow boundary condition types form a group involving the simulation of the interaction of the flow with other flow conditions at the domain boundaries.

5.4.1 Freestream

The freestream boundary condition is intended for use at freestream outer boundaries. This boundary condition uses one-dimensional characteristic theory to set boundary flowfield variables from freestream or flowfield conditions, based on the flow direction at the boundary.

At freestream boundaries with inflow, the HOLD keyword may be used to specify whether total conditions or characteristic values are to be held constant. Total pressure is held constant in both cases, and may result in initial Mach numbers being altered.

For some cases, this boundary condition may also be used at unconfined outflow boundaries, but the `outflow` boundary condition described in Section 5.4.3 is generally recommended instead. In particular, experience has shown that using the `freestream` condition at outflow boundaries with a shear layer exiting the computational domain may result in very slow convergence, and the solution may not be very accurate. There may also be the possibility of a mixed boundary, such as a supersonic outflow with a small subsonic region in the wall boundary layer. In this case, the pressure in the supersonic region is extrapolated to the boundary from upstream, but the pressure in the subsonic region is set from the freestream value. This may cause a small disturbance at the boundary, which can be corrected by specifying the boundary as an `outflow` boundary and imposing a constant pressure for the entire boundary.

Keywords: HOLD

5.4.2 Arbitrary Inflow

The `arbitrary inflow` boundary condition allows conditions to be specified on regions of zonal boundaries where flow is entering the zone. Such a capability may be required to describe a thermally stratified nozzle input flow, or a jet emanating from a wall. The inflow profile may be specified in a number of different ways: as uniform flow, as a point-by-point (xyz) profile, or as uniform flow over a range of grid indices. The ARBITRARY INFLOW keyword is used in the input data file to indicate desired flow properties.

Keywords: ARBITRARY INFLOW

5.4.3 Outflow

The `outflow` boundary condition may be used for internal flows at boundaries where subsonic flow is leaving the computational domain, such as at the exit plane of an inlet, diffuser, or auxiliary flow duct. It is also recommended for downstream outflow boundaries in external flow problems, especially if a shear layer is exiting the computational domain.

Characteristic theory indicates that only one physical condition is required to define the boundary condition. One may know one of the following at the outflow boundary: mass flow, exit pressure, or exit Mach number.

The mass flow (in $\mathrm{lb_m/sec}$) may be specified at the outflow boundary (see the MASS FLOW keyword). The mass flow may be the actual or corrected value. One may alternatively specify the ratio of the desired mass flow to the mass flow through the inflow capture area specified in GMAN. During the solution, the mass flow boundary condition is applied every five iterations by default, which reduces computational costs. The integrated mass flow is compared with the desired value. If the PRESSURE option is used with the MASS FLOW keyword, a spatially-constant pressure is set at the outflow boundary, and modified as the solution proceeds until the desired mass flow is achieved. If the DIRECT option is used, the momentum, and thus the mass flow, is modified directly, and the pressure adjusts as the solution proceeds. For the PRESSURE option, Wind-US displays the ratio between the computational and desired mass flows and the modified pressure at each application of the boundary condition. If you experience difficulty in converging the mass flow, you should consider setting a constant back pressure at the duct exit.

A constant exit pressure may also be specified (see the DOWNSTREAM PRESSURE keyword) at the outflow boundary. This option results in a very reflective boundary condition, which may cause difficulties in convergence of the solution, especially for internal flows. One alternative is to allow the exit pressure to vary spatially according to the distribution of the solution points adjacent to the boundary. This option is selected through the VARIABLE option of the DOWNSTREAM PRESSURE keyword. The UNSTEADY option of the DOWNSTREAM PRESSURE keyword may be used to specify either a sinusoidal or user-defined pressure oscillation at an outflow boundary.

The mass-averaged Mach number may be specified at the outflow boundary using the DOWNSTREAM MACH keyword. This boundary condition is identical to the Chung-Cole compressor face boundary condition discussed below. It simulates the uniform Mach number characteristics that have been observed experimentally at compressor faces. This boundary condition also corresponds to a fairly uniform mass flux through the outflow boundary.

The compressor face models of Chung and Cole (1996) and of Mayer and Paynter (1994) are also available at outflow boundaries, through the COMPRESSOR FACE keyword. Both models are based on the observation that turbine engine conditions set the corrected mass flow, and that this corresponds directly to the average Mach number at the compressor face. These boundary conditions have been implemented mainly for the analysis of unsteady flow; however, they have also been shown to be robust for the establishment of steady-state, supercritical inlet flows.

The computational grid at the outflow boundary should be such that it is modeled with a single computational plane (constant i, j, or k) in a single zone. If two zones merge together near the exit, one should create a small exit zone to accommodate the outflow boundary condition.

Keywords: COMPRESSOR FACE, DOWNSTREAM MACH, DOWNSTREAM PRESSURE, MASS FLOW

5.5 Grid Topology Boundary Conditions

The reflection, self-closing, singular axis, and pinwheel axis types of boundary conditions form a group involving the simulation of the flow at topological surfaces in the grid.

5.5.1 Reflection

The reflection boundary condition simulates a plane of symmetry, and is the same as a solid, slip wall boundary condition. Therefore, within Wind-US, the inviscid wall boundary condition is actually applied. The reflection boundary condition type does provide a descriptive label for the boundary solution points, which may be of use to several auxiliary CFD codes which generate or use reflected grids.

5.5.2 Self-Closing

The self-closing boundary condition can be used at boundaries for which grid lines connect end-to-end (e.g., i_{max} connecting to i_1 as in an O-grid) in a point-match manner. The boundary condition simply averages the flow variables from both sides of the boundary and assigns the average to the two boundaries. This condition was formerly used for polar-type grids in duct flowfields. Note: For best results, one should consider using the coupled boundary condition instead of self-closing.

5.5.3 Singular Axis

The singular axis boundary condition is imposed at locations where an entire or part of a zonal boundary has collapsed to a line (*not a point*). Thus, along the other boundary direction, the grid points are coincident. The singular grid point is evaluated by taking the distance-weighted average of the solution of the adjacent grid points encircling the axis. This boundary condition is not to be used when the singularity line collapses to a point. For partially singular boundaries, the average is computed only over the singular portion of the boundary. Excessive use of this boundary condition is not recommended since flow conservation is not preserved. One should attempt to use non-singular grids whenever possible. TEST 118 allows the choice of which variables are averaged. TEST 150 can be used to explicitly set certain velocity components to zero when the singular axis occurs on symmetry planes. TEST 199 excludes the last grid point on the singular axis from being averaged.

5.5.4 Pinwheel

The pinwheel axis boundary condition is used when there exists multiple singularities at various locations on boundaries. This boundary condition does not zero any velocity components — it simply takes the average. TEST 118 allows the choice of which variables are averaged. TEST 165 allows input of the integer for the order of magnitude of the tolerance for singularity (the default is 10^{-8}).

5.6 Zonal Interface Boundary Conditions

The coupled and chimera boundary condition types involve the interactions between zones of the domain. Periodic boundaries are currently supported only for structured grids, and are treated as a type of coupled boundary condition.

5.6.1 Coupled

The coupled boundary condition is imposed at regions where zones connect. Zone coupling is the name of the process by which Wind-US transfers flowfield information from one zone to another across conterminous computational grid boundaries. This process uses geometric interpolation factors stored in the grid file, which have been previously computed in the GMAN program. The zone interfaces occur at the boundaries of the zones, and so are imposed as boundary conditions at the end of each cycle of the computation.

The default zone coupling algorithm is based on Roe's flux-difference splitting scheme. The COUPLING keyword allows one to change a zone coupling algorithm based on one-dimensional characteristic theory.

Zone boundaries should be treated the same as you would treat interior grid planes; there should not be any large changes in grid stretching or orthogonality at the boundary. In addition, zone boundaries should not be placed in regions of strong flowfield gradients, especially horizontally along jet shear layers or aligned with normal shocks. In other words, use your best engineering judgement in placing zone boundaries in your solution.

Keywords: COUPLING

Periodic Boundaries. Periodic boundaries are currently supported only for structured grids. They are treated as normal coupled boundaries, with the connection data stored in the common grid (*.cgd*) file when setting boundary conditions with GMAN. No keyword is needed in the input data (*.dat*) file.

GMAN's `CONNECT MODE` option is used to specify how to move one boundary surface to overlay it on the corresponding periodic boundary surface. There are two connection modes — translation and rotation. For translation, the user defines the Δx, Δy, and Δz movement for the surface. For rotation the user sets the center of rotation and the angles. GMAN then moves the current boundary surface using the specified method, and attempts to couple the two surfaces together as if they were coexistent boundaries. If successful, it saves the data as normal coupling data for Wind-US. Thus the boundaries look connected even though they are physically separated. The periodic boundary surfaces do not have to be in the same zone, nor do they have to be point matched. They only have to line up physically once the movement has been performed.

Specifically, to set a periodic boundary condition for a structured grid in GMAN:

- In graphics mode, from the main menu select `BOUNDARY COND.`
- Pick the zone and boundary for one of the two periodic boundaries.
- If the boundary condition at the boundary is not `UNDEFINED` (you may select `IDENTIFY POINTS` to check), change it to `UNDEFINED` by doing:
  - Select `MODIFY BNDY`.
  - Select `CHANGE ALL`.
  - Select `UNDEFINED`.
  - From the main menu, select `BOUNDARY COND.`
  - Select `YES-UPDATE FILE`.
- Select `MODIFY BNDY`.
- Select `COUPLE`.
- Select `SEL OTHER BND`.
- Pick the zone and boundary for the other periodic boundary. (Note that no default zone is pre-selected here, even for single-zone grids, so you must select both the zone and boundary.)
- Select `SET COUP MODE`.
- Under `CONNECT MODE`, click on the "`** NONE **`".
- Respond to the prompts at the bottom of the screen to set the connection mode, and to specify the translation or rotation data.
- Select `CONNECT` (not `COUPLE`) to actually connect the two boundaries.

5.6.2 Chimera

The `chimera` boundary condition indicates that the zone boundary is in an overlap region.

5.7 Miscellaneous Boundary Conditions

The `undefined` and `frozen` boundary condition types are included in this section, mostly because they don't fit well in any other section, and are fairly self-explanatory.

5.7.1 Undefined

The default boundary condition type in GMAN is `undefined`. If not set to another boundary condition type, the boundary solution point is evaluated as an average of local solution points. In practice, one should specify the actual boundary condition type for all boundary solution points and avoid having undefined boundary solution points.

If all the points on a boundary surface have an undefined boundary condition, an error message is printed and the solution will abort. If only some points have an undefined boundary condition, a warning message is printed and the solution will continue.

5.7.2 Frozen

The `frozen` boundary condition simply signals a boundary solution point to retain its value as read in from the initial solution file.

6 Convergence Monitoring

Monitoring and properly assessing convergence levels during a Wind-US run are critical in obtaining meaningful, useful results. Wind-US allows you to track convergence by following residuals and/or integrated forces, moments, and mass flow. For engineering applications, the recommended convergence monitoring method is the tracking of integrated quantities of interest. For example, if you are modeling a wing/body geometry to determine drag, you should monitor integrated drag and set some reasonable bounds on drag oscillations as your convergence criterion.

6.1 Residuals

In steady-state (non-time-accurate) solutions, the residuals are the amounts by which the solution vector changes in a single iteration. Ideally, in approaching a steady state solution, the residuals should approach zero. However, in practice, complex geometric and flowfield features may limit the reduction in the residuals to about two orders of magnitude. Wind-US prints solution residuals to the list output file, in order to get a general idea of solution convergence.

For structured grids, Wind-US organizes the equations to be solved into logical "groups" that are solved together. For example, when a one- or two-equation turbulence model is used, the Navier-Stokes equations and the turbulence model equations are in two separate groups.

For each equation group in each zone, Wind-US prints the zone number, cycle number, location of the maximum residual (i, j, and k indices), equation number for which the maximum residual occurred, the value of the maximum residual, and the L2-norm of all the residuals for all the equations over all the points in that zone. The L2-norm of the residuals will give you an idea of the overall convergence of the solution. The location of the maximum residual may give you insight into problems with a particular solution. After solution "bombs" or when convergence is unacceptably slow, the location of the maximum residual is the first place you should look for potential problems with the solution.

The residuals are printed by default each iteration. The output interval may be changed, however, using the `CYCLES` and `ITERATIONS` keywords. Residuals may also be plotted by first using the auxiliary program *resplt* to generate a GENPLOT file, then using that file as input to the `plot` command in the CFPOST post-processing package.

By default, if the maximum residual for an equation group decreases by four orders of magnitude in a particular zone, a "converged" message is printed in the list output file, and iterations for that group in that zone are ended for the current cycle. Note that, if the residuals early in the calculation are large due to large initial solution transients, Wind-US may decide that a zone is converged when it may require significantly more iterations. In the input data file, with the `CONVERGE` keyword you can specify different convergence criteria, by setting the amount the residual must decrease, and by telling Wind-US to use the value of the residual rather than an order-of-magnitude reduction. You can also specify use of the L2-norm of the residual instead of the maximum residual using `TEST 128`.

Keywords: `CONVERGE`, `CYCLES`, `ITERATIONS`, `TEST 128`

6.2 Integrated Flowfield Quantities

As noted above, the optimal convergence checking criterion for a solution is an integrated quantity of interest for a particular study. For example, for an afterbody drag study to calculate pressure drag, the integrated drag is obviously the best quantity to track in monitoring convergence. This may be accomplished using Wind-US's flowfield integration capability. In the input data file, you may specify a number of computational surfaces for which Wind-US will integrate forces, moments, and/or mass flows. If you specify reference length, area, and moment center, Wind-US will output the forces and moments as coefficients; you may even specify output of lift and drag coefficients in place of x and y force coefficients.

You may specify zones and computational grid indices of subsets to be integrated, and you may request that different quantities be integrated on each subset. You may also control the frequency of output and whether the code outputs subset totals and/or zonal and grand totals. The auxiliary program *resplt* will produce GENPLOT plot files of output integration quantities versus solution cycle number, which may then be used as input to the `plot` command in the CFPOST post-processing package.

Keywords: `LOADS`

6.3 History Tracking of Flow Data

In time-accurate calculations, where a constant time step is being specified and is the same throughout the flow field, you may wish to track a particular flow variable as the solution advances in time. For example, you may be interested in monitoring the static pressure on a backward-facing step as vortices roll off the back of the step. You may request history tracking in the input data file. Specification must include zone numbers and ranges of grid points to track, and the frequency of the sampling. When you request history tracking, Wind-US creates a time history file containing the sampled data. The auxiliary program *thplt* must be run to extract data from the history file into GENPLOT plot files, which may then be used as input to the `plot` command in the CFPOST post-processing package.

Keywords: `HISTORY`

7 Files

A number of files are used by Wind-US in the course of a solution. The script file you run to submit Wind-US jobs will assign all the necessary files to their appropriate Fortran unit numbers, so you should not need to do any of that yourself. Each of the support files is described briefly below.

7.1 Input Data File (*.dat*)

Fortran unit number 5

The *input data file* is the primary control file for Wind-US and must be created for each case you want to run with the code. Input data and code options are entered through the use of descriptive keywords in this file. You should observe the following formatting rules in creating the input data file:

1. The first three lines of the file are reserved for geometry, flow condition, and arbitrary titles, respectively. Each of these titles may be up to 64 characters long. None of these first three lines may start with the (case-insensitive) word “Include”.

2. Comment lines, beginning with a ‘/’ character, may be placed anywhere in the file after the first three lines. Data file readability may be improved dramatically through the liberal use of comments — for example, separating logical sections of the data file: numerical algorithm, force integrations, test options, etc.

3. Block data, such as that specified in arbitrary inflow or chemistry cases, must be contiguous — only keywords corresponding to the block may reside between the beginning and ending block indicators (e.g., `CHEMISTRY` and `ENDCHEMISTRY`).

4. Keywords may be entered in upper or lower case.

5. Abbreviations for keywords may be used, as long as they are unique. If they are not, you may not get the results you expect. For example, it’s not a good idea to use single-letter abbreviations for keywords.

The following is an example of a simple input data file:

```
Geometric Title
Flowfield Condition Title
Optional Title
Freestream static 0.9 14.7 530. 4. 0.
Cycles 15
Inviscid
End
```

7.2 Grid File (*.cgd*)

Fortran unit number 11

The computational grid used by Wind-US for a particular case is stored in the *grid file.* In this file are stored the (x, y, z) coordinates of all computational grid points, zone coupling interpolation factors, and grid reference and scaling data.

This file was originally referred to as the *common* grid file, so named because the file was formatted according to Boeing's Common File Format (CFF). Wind-US also supports grid files in CGNS (CFD General Notation System) format.[13] Both common files and CGNS files are binary, and portable to virtually every hardware platform, except Cray, with no need for explicit data conversions.

Grid files for Wind-US may be created by several mesh-generation codes in either common file or CGNS format. If necessary, the *cfcnvt* utility may be used to convert a variety of other formats, including PLOT3D xyz format, to common file format.

Zone coupling, reference, and scaling data are added to common grid files using the GMAN program. Common grid files are also used in the CFPOST post-processing package. Neither GMAN nor CFPOST currently support CGNS files, however.

Keywords: `CGNSBASE`

7.3 Flow File (*.cfl*)

Fortran unit number 20

The *flow file* contains the computed flow field. For Navier-Stokes and Euler solutions, the file contains density, momentum, and energy data, and, for viscous solutions, turbulence data. The flow file also records the current solution cycle number to allow the file to be used for solution restarts.

Like the grid file, the flow file was originally referred to as the *common* flow file, but may now be written in either common file or CGNS format. Several graphical post-processing programs are able to read both common files and CGNS files.

The CFPOST post-processing package may be used with common flow files to produce other files for post-processing and/or to create flowfield plots directly. CFPOST does not currently support CGNS files, however.

Keywords: `CGNSBASE`

7.4 Boundary Data File (*.tda*)

Fortran unit number 14

Wind-US's *boundary data file* is used during solution restarts, and results in smoother restarts, especially with higher-order boundary coupling. The file acts as a buffer for the transfer of zone coupling information and a holding bin for data needed throughout a Wind-US run but not stored in the grid or solution file.

7.5 Time History File (*.cth*)

Fortran unit number 19

The *time history file* is a common file which stores data resulting from the use of Wind-US's history tracking capability. The file contains a lookup table corresponding to the range of computational indices tracked during the run, time stamp data, and flowfield data for each time stamp.

[13] Detailed information on the CGNS standard may be found at the CGNS web site, at http://cgns.sourceforge.net/.

Upon completion of a time history run, the auxiliary program *thplt* may be used to view the contents of the time history file.

Keywords: `HISTORY`

7.6 List Output File (*.lis*)

Fortran unit number 6

The purpose of Wind-US's *list output file* is to echo the input from the input data file, track convergence and integration results, record CPU/job statistics, and log code error messages. The auxiliary program *resplt* may be used to extract convergence and integration data from the list output file and create a GENPLOT-style data file, which may be plotted with the `plot` command in the CFPOST post-processing package. For parallel-processing runs, this file also contains messages relating to the PVM system and to the allocation and operation of slave processors. Convergence data is written to this file for each of the equation sets solved during the run, including the Euler, Navier-Stokes, and non-algebraic turbulence model sets.

7.7 Wind-US Stop File (*NDSTOP*)

Fortran unit number 1

The *stop file* is used to stop Wind-US execution cleanly in the middle of a CFD solution. Although a solution may be stopped simply by killing the Wind-US process from the system queue, doing so will not ensure a clean update of all zonal flowfield data to the flowfield file. The stop file — named *NDSTOP* — provides a means to cleanly shut down a running solution, completing the current cycle or zone, performing zone coupling, updating the flowfield file, and removing all symbolic links to Fortran file unit numbers.

To stop the code, you must place one of two words in the stop file in the directory in which the Wind-US job is running. The word `STOP` in the stop file signals Wind-US to complete the current cycle (at the end of the last zone) and exit. In single-processing mode, you may also use the word `STOPZONE` in the stop file to stop Wind-US after completing the zone currently in memory.[14] You may then restart the code in your next run, starting at the next zone or back at zone one. Regardless of the existence of this file, Wind-US will stop if the requested number of cycles has been computed, or if your solution has converged.

During the clean-up procedure at the end of the job, the *NDSTOP* file is automatically removed.

Note that the directory in which the Wind-US job is running, where the *NDSTOP* file must be, is not necessarily the one you were in when the *wind* command was issued. If you don't use the *-runinplace* option to the *wind* script (see Section 8.1), the job will be run in a remote directory. The root name of the remote run directory may be specified using the *-runroot* option, or in response to a command line prompt. The default for the "root name" of the remote directory is */tmp*. The full name of the remote directory will be *rootname/userid/basename.scr*, where *rootname* is the root name described above, *userid* is your userid, and *basename* is the base name of your *.dat* file.

On a Unix system, you might submit a simple 'at' job for a later time as follows:

```
at 0530 monday
echo STOP > NDSTOP
^D
```

[14] In multi-processing mode, `STOPZONE` does the same thing as `STOP`.

At 5:30 AM on the next Monday, the system would create the *NDSTOP* file with the word '`STOP`' in it. Note that this will not stop the run exactly at 5:30 AM; Wind-US must still complete the current cycle, which may take an hour or more for large cases.

Keywords: `RESTART`

7.8 Temperature and Transition Specification Files

Fortran unit number 45

Wind-US can read temperature and transition files, specifying the temperature or transition to turbulence on any boundary surface, that were created with the older *tmptrn* utility. This option is included for backward compatibility with WIND 2.0, and is only needed for an initial (i.e., non-restart) run. The *wind* script copies the files to the run directory, and Wind-US opens the files directly (unit 45) using the file names specified with the `TTSPEC` keyword.

New applications should use the latest *tmptrn* utility to write the temperature/transition data into the common flow (*.cfl*) file directly.

Keywords: `TTSPEC`

7.9 Chemistry Files (*.chm*)

Fortran unit number 26

The generalized chemistry files contain all the information Wind-US requires to compute a general chemistry mixture. A chemistry file has a header line, followed by three sections containing thermodynamic coefficients, finite rate coefficients, and transport properties.

7.9.1 Header

The header line must contain a single parameter, *ispec*, specifying the type of reaction rate and the format for the finite rate data. The format for the header line is[15]:

ispec `ISPEC`

where

ispec	Reaction Rate and Format
1, 4, 100, 110	Forward and backward rates from equilibrium constant polynomial, Format 1
3, 130	Forward and backward rates, Format 2
120	Forward rate only, Format 3

7.9.2 Thermodynamic Coefficients

This section of the chemistry data file contains the information necessary to compute the thermodynamic properties for each species. The general format for this section is:

[15] The parameter *ispec* is read using a list-directed read statement. The `ISPEC` label following the value is thus optional, but present in the standard chemistry files supplied with Wind-US. The labels following the parameters *ns*, *nreq*, *ndeq*, and *tfrmin*, described in Section 7.9.2 and Section 7.9.3, are also optional.

```
THERMODYNAMIC COEFFICIENTS
Title, line 1
Title, line 2
ns       NS
Curve type
Information defining species 1
. . .
Information defining species ns
```

where *ns* is the number of species, and *Curve type* specifies the type of curve fits used to define the thermodynamic properties. The *Curve type* line may be omitted (not left blank), or specified as one of `SPARKCRV`, `WINDNASA`, and `NASA3287`. If the line is omitted, the `SPARKCRV` curve type is assumed.

The information defining each species, and the specific format used, depends on the curve type, as described below.

`SPARKCRV`. This is the original file format used for Wind-US chemistry files. The specific heat at constant pressure C_p for each species is defined by a series of fourth-order polynomials, each valid within a defined temperature range. I.e.,

$$\frac{C_p}{R} = a_1 + a_2 T + a_3 T^2 + a_4 T^3 + a_5 T^4 \tag{1}$$

where R is the universal gas constant, and T is in K.

For each species, the information defining the species and for computing C_p/R, etc., is stored in the *.chm* file as described in the following table. Note that records 2–3 are repeated for each temperature range.

Record	Contents	Columns	Format
1	Name of species	1–8	`a8`
	Number of curves (i.e., temperature ranges) defining C_p/R	16–20	`i5`
	Name, and number per molecule, of constituent elements	25–44	`4(a2,f3.0)`
	The ratio C_p/R	51–60	`f10.1`
	Molecular weight	66–75	`f10.3`
2	Beginning and ending temperature for curve	1–30	`2e15.5`
	Coefficients a_1–a_3 in equation (1)	31–75	`3e15.5`
3	Coefficients a_4–a_5 in equation (1)	1–30	`2e15.5`
	Heat of formation at 298.15 K, in J/mole	31–45	`e15.5`
	Gibb's free energy	46–60	`e15.5`

Example

```
THERMODYNAMIC COEFFICIENTS
 FROM NASA-RFL-TR-70-3, NASA-CR-111989, MAC LIB FISH NO. N71-38747
```

```
    5      NS
SPARKCRV
O2                 3    O  2.   0.   0.   0.             3.5         32.000
        300.000       1000.000    0.37190E+01   -0.25170E-02    0.85840E-05
   -0.83000E-08    0.27080E-11  -0.104419E+04    0.00000E+00
       1000.000       6000.000    0.33160E+01    0.11510E-02   -0.37260E-06
    0.61860E-10   -0.36660E-14  -0.104419E+04    0.00000E+00
       6000.000      15000.000    0.37210E+01    0.42540E-03   -0.28350E-07
    0.60500E-12   -0.51860E-17  -0.104419E+04    0.00000E+00
NO                 3    O  1.N  1.   0.   0.             3.5         30.008
        300.000       1000.000    0.41470E+01   -0.41200E-02    0.96920E-05
   -0.78630E-08    0.22310E-11   0.979001E+04    0.00000E+00
       1000.000       6000.000    0.32210E+01    0.12210E-02   -0.42970E-06
    0.65590E-10   -0.34510E-14   0.979001E+04    0.00000E+00
       6000.000      15000.000    0.38450E+01    0.25210E-03   -0.26580E-07
    0.21620E-11   -0.63810E-16   0.979001E+04    0.00000E+00
```
... *etc.*

`WINDNASA`. This is a modified form of the SPARK curve fits described above. The specific heat at constant pressure for each species is again defined by a series of fourth-order polynomials, each valid within a defined temperature range. I.e.,

$$\frac{C_p^0}{R} = a_1 + a_2 T + a_3 T^2 + a_4 T^3 + a_5 T^4 \tag{2}$$

where R is the universal gas constant, and T is in K.

In addition, the enthalpy and entropy are computed as

$$\frac{H^0}{RT} = a_1 + a_2 \frac{T}{2} + a_3 \frac{T^2}{3} + a_4 \frac{T^3}{4} + a_5 \frac{T^4}{5} + \frac{a_6}{T} \tag{3}$$

$$\frac{S^0}{R} = a_1 \ln T + a_2 T + a_3 \frac{T^2}{2} + a_4 \frac{T^3}{3} + a_5 \frac{T^4}{4} + a_7 \tag{4}$$

For each species, the information defining the species and for computing C_p^0/R, etc., is stored in the *.chm* file as described in the following table. Note that records 2–3 are repeated for each temperature range.

Record	Contents	Columns	Format
1	Name of species	1–8	`a8`
	Number of curves (i.e., temperature ranges) defining C_p^0/R	16–20	`i5`
	Name, and number per molecule, of constituent elements	25–44	`4(a2,f3.0)`
	The ratio C_p/R	51–60	`f10.1`
	Molecular weight	66–75	`f10.3`
2	Beginning and ending temperature for curve	1–30	`2e15.5`
	Coefficients a_1–a_3 in equations for thermodynamic properties	31–75	`3e15.5`
3	Coefficients a_4–a_7 in equations for thermodynamic properties	1–60	`4e15.5`
4	Identifier string starting with the word “Heat”	1–31	`a31`
	Heat of formation at 0 K, in J/mole	32–46	`f15.3`

Example

```
THERMODYNAMIC COEFFICIENTS
 CURVE FITS FROM NASA LEWIS CET86 HIGH TEMPERATURE THERMO DATA BASE

    7      NS
WINDNASA
O2                 2    O  2.   0.   0.   0.             3.5         31.998
        300.000       5000.000  3.1162949E+00  1.5886094E-03 -6.7904360E-07
  1.4714899E-10 -1.1729212E-14 -9.9401794E+02  6.4600671E+00
       5000.000      15000.000  2.5782323E+00  8.5796324E-04 -7.6397647E-08
  1.3412616E-12  3.2564804E-17  1.1504711E+03  1.1400551E+01
Heat of Formation at 0 deg K    0.0
H                  2    H  1.   0.   0.   0.             2.5          1.008
        300.000       5000.000  2.5000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00  0.0000000E+00  2.5474038E+04 -4.5991986E-01
       5000.000      15000.000  2.5000000E+00  0.0000000E+00  0.0000000E+00
  0.0000000E+00  0.0000000E+00  2.5474038E+04 -4.5991986E-01
Heat of Formation at 0 deg K    216024.1
... etc.
```

`NASA3287`. This format for the curve fits defining the thermodynamic properties is derived from the one defined in NASA TP 3287 (McBride, Gordon, and Reno, 2001). A series of curves is again used to define the specific heat at constant pressure, enthalpy, and entropy, with each curve valid within a defined temperature range. I.e.,

$$\frac{C_p^0}{R} = a_1T^{-2} + a_2T^{-1} + a_3 + a_4T + a_5T^2 + a_6T^3 + a_7T^4 + a_8T^5 \tag{5}$$

$$\frac{H^0}{RT} = -a_1T^{-2} + a_2T^{-1}\ln T + a_3 + a_4\frac{T}{2} + a_5\frac{T^2}{3} + a_6\frac{T^3}{4} + a_7\frac{T^4}{5} + a_8\frac{T^5}{6} + \frac{b_1}{T} \tag{6}$$

$$\frac{S^0}{R} = b_2 - a_1\frac{T^{-2}}{2} - a_2T^{-1} + a_3\ln T + a_4T + a_5\frac{T^2}{2} + a_6\frac{T^3}{3} + a_7\frac{T^4}{4} + a_8\frac{T^5}{5} \tag{7}$$

where R is the universal gas constant, and T is in K.

For each species, the information defining the species and for computing C_p^0/R, etc., is stored in the *.chm* file as described in the following table. Note that records 3–5 are repeated for each temperature range.

Record	Contents	Columns	Format
1	Name of species	1–18	`a18`
	Comments (not used in Wind-US)	19–76	`a58`
2	Number of curves (i.e., temperature ranges) defining C_p^0/R	1–2	`i2`
	Identification code (not used in Wind-US)	4–9	`a6`
	Name, and number per molecule, of constituent elements	11–50	`5(a2,f6.2)`
	Flag indicating standard state (not used in Wind-US)	52	`i1`
	Molecular weight	53–65	`f13.5`
	Heat of formation at 298.15 K, in J/mole	66–80	`f15.3`
3	Beginning and ending temperature for curve	2–21	`2f10.3`
	Number of coefficients a_n in equation (5)	23	`i1`
	Exponents of T in equation (5)	24–63	`8f5.1`
	Enthalpy difference from 298.15 K to 0 K, in J/mole	66–80	`f15.3`
4	Coefficients a_1–a_5 in equations for thermodynamic properties	1–80	`5d16.8`
5	Coefficients a_6–a_8 in equations for thermodynamic properties	1–48	`3d16.8`
	Coefficients b_1 and b_2 in equations for thermodynamic properties	49–80	`2d16.8`
6	Identifier string starting with the word "Heat"	1–31	`a31`
	Heat of formation at 0 K, in J/mole	32–46	`f15.3`

Example

```
THERMODYNAMIC COEFFICIENTS
```

```
 CURVE FIT JANAF 6000K DATA EXTRAP. TO 15000K & NASA LEWIS DATA RE-FITTED

    5      NS
NASA3287
CO2               Props & Hf298: TPIS v2,pt1,1991,p27.
 3 l 7/88 C   1.00O   2.00    0.00    0.00    0.00 0     44.00980    -393510.000
    200.000  1000.000 7 -2.0 -1.0  0.0  1.0  2.0  3.0  4.0  0.0         9365.469
  4.94378364D+04 -6.26429208D+02  5.30181336D+00  2.50360057D-03 -2.12470010D-07
 -7.69148680D-10  2.84997991D-13  0.00000000D+00 -4.52818986D+04 -7.04876965D+00
   1000.000  6000.000 7 -2.0 -1.0  0.0  1.0  2.0  3.0  4.0  0.0         9365.469
  1.17696943D+05 -1.78880147D+03  8.29154353D+00 -9.22477831D-05  4.86963541D-09
 -1.89206384D-12  6.33067509D-16  0.00000000D+00 -3.90834501D+04 -2.65268192D+01
   6000.000 20000.000 7 -2.0 -1.0  0.0  1.0  2.0  3.0  4.0  0.0         9365.469
 -1.54440594D+09  1.01683595D+06 -2.56137666D+02  3.36936340D-02 -2.18115756D-06
  6.99132366D-11 -8.84221052D-16  0.00000000D+00 -8.04312703D+06  2.25415288D+03
Heat of Formation at 0 deg K    -393149.56
H2O               CODATA,1989. JRNBS v92,1987,p35. TRC tuv-25,10/88.
 2 l 8/89 H   2.00O   1.00    0.00    0.00    0.00 0     18.01528    -241826.000
    200.000  1000.000 7 -2.0 -1.0  0.0  1.0  2.0  3.0  4.0  0.0         9904.092
 -3.94795999D+04  5.75572977D+02  9.31783351D-01  7.22271091D-03 -7.34255448D-06
  4.95504134D-09 -1.33693261D-12  0.00000000D+00 -3.30397425D+04  1.72420539D+01
   1000.000  6000.000 7 -2.0 -1.0  0.0  1.0  2.0  3.0  4.0  0.0         9904.092
  1.03497224D+06 -2.41269895D+03  4.64611114D+00  2.29199814D-03 -6.83683007D-07
  9.42646842D-11 -4.82238028D-15  0.00000000D+00 -1.38428625D+04 -7.97815119D+00
Heat of Formation at 0 deg K    -238918.95
```

... *etc.*

7.9.3 Finite Rate Coefficients

This section of the file contains the reaction rate information. The first five lines are:

`FINITE RATE COEFFICIENTS`

Title, line 1

Title, line 2

nreq ndeq   `NREQ, NDEQ`

tfrmin   `TFRMIN`

where *nreq* is the total number of reactions (dissociation + exchange + ionization), *ndeq* is the number of dissociation reactions (i.e., have a third body), and *tfrmin* is the temperature in K below which no reactions occur.

There are three possible formats for the remainder of this section, depending on the value of *ispec*.

Format 1; *ispec* = 1, 4, 100–119. This option may be used for any chemically reacting flow. Information is specified defining the forward reaction rate k_f and the equilibrium constant K. The rates themselves are computed using the equations

$$\begin{aligned}
k_f &= CT^S e^{-D/(\kappa T)} && (8)\\
k_b &= k_f/K && (9)\\
K &= \exp\left(a_1 + a_2 Z + a_3 Z^2 + a_4 Z^3 + a_5 Z^4\right) && (10)\\
Z &= 10{,}000/T && (11)
\end{aligned}$$

where T is the temperature in K, the ratio D/κ is in K, and κ is the Boltzmann constant. The reaction rate coefficient C has units (cm^3/g-mol)(sec-K^S)$^{-1}$.

The various parameters and polynomial coefficients are read from the chemistry data file, in the following form:

Information defining dissociation reaction 1
. . .
Information defining dissociation reaction ndeq
Information defining exchange reaction 1
. . .
Information defining exchange reaction nreq - ndeq

where *nreq* is the total number of reactions, and *ndeq* is the number of dissociation reactions.

For each reaction, the information defining the reaction and for computing the reaction rates is stored in the *.chm* file as described in the following table. Note that for dissociation reactions using variable third-body reaction rates, record 3 is repeated for each third body reactant. Otherwise, record 3 appears only once.

Record	Contents	Columns	Format
1	Name of first reactant	1–5	`a5`
	Name of second reactant (blank for dissociation)	9–13	`a5`
	Name of first product	17–21	`a5`
	Name of second product	25–29	`a5`
	Temperature exponent S in equation (8)	33–44	`e12.4`
	D/κ in equation (8)	45–56	`e12.4`
2	Coefficients a_1–a_5 in equation (10)	1–60	`5e12.4`
	Number of third body reactants, or 0 for exchange and ionization reactions. For dissociation reactions, this must be either 1 (if an average third-body reaction rate is being used) or the number of species *ns* (if variable third-body reaction rates are being used).	61–64	`i4`
3	Name of third body reactant. Only needed if variable third-body reaction rates are being used.	17–24	`a8`
	Reaction rate coefficient. For dissociation reactions, this is either the average third-body reaction rate coefficient, or the reaction rate coefficient for the specified third body reactant.	25–36	`e12.4`

With Format 1, the data is read in subroutine `frtin1`, and the rates are computed in `rates1` (for *ispec* = 1), `rates4` (*ispec* = 4), `rates` (*ispec* = 100), or `ratesa` (*ispec* = 110).[16]

Example

```
FINITE RATE COEFFICIENTS
 FROM AIAA 88-0513

    5,3      NREQ,NDEQ
  2000.      TFRMIN
O2              O       O         -1.0       5.9500E+04
   1.335      -4.127     -0.616        0.093     -0.005       5
                O2       2.75E+19
                NO       2.75E+19
                O        8.25E+19
                N        8.25E+19
                N2       2.75E+19
N2              N       N         -1.6       1.1320E+05
   3.898     -12.611       0.683      -0.118       0.006       5
                O2       3.70E+21
                NO       3.70E+21
                O        1.11E+22
                N        1.11E+22
                N2       3.70E+21
NO              N       O         -0.5       7.5500E+04
   1.549      -7.784       0.228      -0.043       0.002       5
                O2       2.30E+17
                NO       2.30E+17
                O        4.60E+17
                N        4.60E+17
                N2       2.30E+17
NO      O       O2      N          1.29      1.9220E+04
   0.215      -3.652       0.843      -0.136       0.007       0
                         2.16E+08
O       N2      NO      N          0.1       3.7700E+04
   2.349      -4.828       0.455      -0.075       0.004       0
                         3.18E+13
```

Format 2; *ispec* = 3, 130–139. This option is similar to the previous one, except that the forward and backward reaction rates are computed separately, using the equations

$$k_f = C_f T^{S_f} e^{-D_f/(\kappa T)} \tag{12}$$

$$k_b = C_b T^{S_b} e^{-D_b/(\kappa T)} \tag{13}$$

where T is the temperature in K, the ratios D_f/κ and D_b/κ are in K, and κ is the Boltzmann constant. The reaction rate coefficients for the j'th reaction, $(C_f)_j$ and $(C_b)_j$, have units

$$(C_f)_j\colon \quad \left(\frac{\text{cm}^3}{\text{g-mol}}\right)^{O_j-1} \frac{1}{\text{sec-K}^{S_f}}, \qquad (C_b)_j\colon \quad \left(\frac{\text{cm}^3}{\text{g-mol}}\right)^{O_j-1+\nu_j} \frac{1}{\text{sec-K}^{S_b}}$$

[16] At some point, the special-case options *ispec* = 1 and 4 may be eliminated in favor of one of the more general *ispec* = 100–119 options.

where O_j is the order of the reaction (i.e., the total number of moles of reactants), and ν_j is the number of moles of products minus the number of moles of reactants.

The various parameters are read from the chemistry data file, in the following form:

Information defining dissociation reaction 1
. . .
Information defining dissociation reaction ndeq
Information defining exchange reaction 1
. . .
Information defining exchange reaction nreq - ndeq

where *nreq* is the total number of reactions, and *ndeq* is the number of dissociation reactions.

For each reaction, the information defining the reaction and for computing the reaction rates is stored in the *.chm* file as described in the following table.

Record	Contents	Columns	Format
1	Name and number of molecules of first reactant	1–8	`a5,f3.1`
	Name and number of molecules of second reactant (blank for dissociation)	9–16	`a5,f3.1`
	Name and number of molecules of first product	17–24	`a5,f3.1`
	Name and number of molecules of second product	25–32	`a5,f3.1`
	Temperature exponent S_f in equation (12)	33–44	`e12.4`
	D_f/κ in equation (12)	45–56	`e12.4`
	Reaction rate coefficient C_f in equation (12)	57–68	`e12.4`
2	Temperature exponent S_b in equation (13)	33–44	`e12.4`
	D_b/κ in equation (13)	45–56	`e12.4`
	Reaction rate coefficient C_b in equation (13)	57–68	`e12.4`

With Format 2, the data is read in subroutine `frtin3`, and the rates are computed in `rates3` (for *ispec* = 3), or `ratesb` (*ispec* = 130).[17]

Example

```
FINITE RATE COEFFICIENTS
 FROM EVAN & SCHEXNAYDER - CONVERTED TO EQUILIBRIUM CONSTANT FORM

   8,4      NREQ,NDEQ
  300.      TFRMIN
O2   1.        O    1. O    1.   -1.0        5.9340E+04   7.20E+18
                                 -1.0        0.0          4.00E+17
H2   1.        H    1. H    1.   -1.0        5.1987E+04   5.50E+18
                                 -1.0        0.0          1.80E+18
H2O  1.        OH   1. H    1.   -1.5        5.9386E+04   5.20E+21
```

[17] At some point, the special-case option *ispec* = 3 may be eliminated in favor of one of the more general *ispec* = 130–139 options.

```
                                  -1.5       0.0          4.40E+20
OH   1.          O    1. H    1.  -1.0       5.0830E+04   8.50E+18
                                  -1.0       0.0          7.10E+18
O2   1. H    1. OH   1. O    1.    0.0       8.4550E+03   2.20E+14
                                   0.0       0.0          1.50E+13
H2   1. O    1. OH   1. H    1.    0.0       5.5860E+03   7.50E+13
                                   0.0       4.4290E+03   3.00E+13
H2O  1. O    1. OH   1. OH   1.    0.0       9.0590E+03   5.80E+13
                                   0.0       5.0300E+02   5.30E+12
H2O  1. H    1. OH   1. H2   1.    0.0       1.0116E+04   8.40E+13
                                   0.0       2.6000E+03   2.00E+13
```

Format 3; *ispec* = 120–129. This option is only for global 1- or 2-reaction chemistry, and only for forward reactions. It is a quick method for simulating detonation problems, for example, in which reactions proceed only forward to completion. The forward reaction rates are computed using the equation

$$k = CT^{S}e^{-D/(\kappa T)} \tag{14}$$

where T is the temperature in K, the ratio D/κ is in K, and κ is the Boltzmann constant. The reaction rate coefficient for the j'th reaction, C_j, has units $(\text{cm}^3/\text{g-mol})^{O_j-1}(\text{sec-K}^S)^{-1}$, where O_j is the order of the reaction (i.e., the total number of moles of reactants). There are no backward reactions.

The various parameters are read from the chemistry data file, in the following form:

Information defining reaction 1
. . .
Information defining reaction nreq

where *nreq* is the total number of reactions.

For each reaction, the information defining the reaction and for computing the reaction rates is stored in the *.chm* file as described in the following table.

Record	Contents	Columns	Format
1	Name and number of molecules of first reactant	1–8	`a5,f3.1`
	Name and number of molecules of second reactant (blank for dissociation)	9–16	`a5,f3.1`
	Name and number of molecules of first product	17–24	`a5,f3.1`
	Name and number of molecules of second product	25–32	`a5,f3.1`
	Temperature exponent S in equation (14)	33–44	`e12.4`
	D/κ in equation (14)	45–56	`e12.4`
2	Place holders for future use. Leave blank.		
3	Exponents on concentration of first and second reactants	1–16	`2f8.3`
	Reaction rate coefficient C in equation (14)	25–36	`e12.4`

With Format 3, the data is read in subroutine `frtin2`, and the rates are computed in `ratesf`.

Example

```
FINITE RATE COEFFICIENTS
WESTBROOK-DREYER GLOBAL REACTION MODEL

    1,0      NREQ,NDEQ
   250.      TFRMIN
C2H4 1. O2   3. CO2  2. H2O  2.    0.0       1.5098E+04

0.10    1.65             2.00E+12
```

7.9.4 Transport Coefficients

This section of the chemistry data file contains the coefficients used to compute the laminar viscosity and thermal conductivity. The formulation is based on Wilke's law which uses Sutherland's law individually for each species. Thus for each species, there are equations of the following form, each valid within a defined temperature range:

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_{0\mu}}\right)^{\frac{3}{2}} \frac{T_{0\mu} + S_\mu}{T + S_\mu} \qquad (15)$$

$$\frac{\kappa}{\kappa_0} = \left(\frac{T}{T_{0\kappa}}\right)^{\frac{3}{2}} \frac{T_{0\kappa} + S_\kappa}{T + S_\kappa} \qquad (16)$$

The various parameters are read from the chemistry data file, in the following form:

`TRANSPORT COEFFICIENTS`
Title, line 1
Title, line 2
Information for species 1
. . .
Information for species ns

For each species, the information is stored in the *.chm* file as described in the following table. Note that records 3–4 are repeated for each temperature range after the first.

In the file, the reference viscosity μ_0 is in millipoise; the reference conductivity k_0 is in BTU/(hour-ft-°R); the reference temperatures and temperature offsets are in °R; and the beginning and ending temperatures for each curve are in K.

Record	Contents	Columns	Format
1	Name of species	1–8	`a8`
	Number of curves (i.e., temperature ranges) defining μ and k	11–15	`i5`
	Beginning and ending temperature for first curve	16–35	`2f10.3`
	Reference viscosity μ_0 for first curve	37–48	`e12.4`
	Reference temperature $T_{0\mu}$ for first curve	49–60	`e12.4`
	Reference temperature offset S_μ for first curve	61–72	`e12.4`
2	Reference conductivity k_0 for first curve	37–48	`e12.4`
	Reference temperature T_{0k} for first curve	49–60	`e12.4`
	Reference temperature offset S_k for first curve	61–72	`e12.4`
3	Beginning and ending temperature for curve	16–35	`2f10.3`
	Reference viscosity μ_0 for curve	37–48	`e12.4`
	Reference temperature $T_{0\mu}$ for curve	49–60	`e12.4`
	Reference temperature offset S_μ for curve	61–72	`e12.4`
4	Reference conductivity k_0 for curve	37–48	`e12.4`
	Reference temperature T_{0k} for curve	49–60	`e12.4`
	Reference temperature offset S_k for curve	61–72	`e12.4`

Example

```
TRANSPORT COEFFICIENTS


O2            1   300.000 15000.000   1.9190E-01  4.9160E+02  2.5000E+02
                                      1.4190E-02  4.9160E+02  4.0000E+02
NO            1   300.000 15000.000   1.3700E-01  4.9160E+02  4.0000E+02
                                      8.4070E-03  4.9160E+02  4.0000E+03
O             1   300.000 15000.000   1.7030E-01  7.5000E+02  1.5500E+03
                                      1.0360E-02  4.9160E+02  2.3000E+03
N             1   300.000 15000.000   1.7890E-01  4.9160E+02  2.3000E+02
                                      6.8900E-02  4.9160E+02  2.3030E+02
N2            1   300.000 15000.000   1.6630E-01  4.9160E+02  1.9200E+02
                                      1.4000E-02  4.9160E+02  3.0000E+02
```

Keywords: `CHEMISTRY`

7.10 Reserved Files

Unit numbers 15, 21, and 55 are reserved for proprietary features, and should not be used by Wind-US developers.

8 Scripts

Wind-US is run using a Unix script which attaches appropriate files and either starts Wind-US interactively or submits the job to a queueing system. In addition, this script checks for special files and may be used to re-invoke Wind-US after performing intermediate operations.

8.1 *wind* — Run Wind-US

The usual procedure for running Wind-US is via a command-line script called *wind*. With this approach, the specific executable to be run (e.g., production version, alpha version, etc.), the names of the required input and output files, etc., may be defaulted, specified on the command line, or entered as responses to prompts. The various options to the script are described below in the form of a Unix-style man page for *wind*.

If the *Tcl/Tk* interpreter is available, Wind-US may be launched via an interactive GUI by using **-g** as the first option to the *wind* script, i.e., by typing `wind -g`. In this case, the executable to be run, the file names, etc., are specified via the GUI. Any options to the *wind* script following the **-g** are ignored. If the **-g** option is specified, but the *Tcl/Tk* interpreter is not available, the usual command-line interface will be used.

The *wind* Man Page

NAME

wind — a computational platform for solving various sets of equations governing fluid dynamics

SYNOPSIS

wind [**-batch**] [**-begtime** *time*] [**-binroot** *directory*] [**-cfdrootrem** *directory*] [**-dat** *datfile*] [**-debug**] [**-debugger** *debugger*] [**-endtime** *time*] [**-flow** *cflfile*] [**-g**] [**-grid** *cgdfile*] [**-grpcharge** *number*] [**-help**] [**-list** *lisfile*] [**-memory** *number*] [**-mp**] [**-mpmode** *mode*] [**-ncpu** *number*] [**-nice_val** *number*] [**-nobg**] [**-(no)parallel**] [**-not_nice**] [**-nzones** *number*] [**-program** *windname*] [**-queue_name** *name*] [**-remoterun**] [**-runinplace**] [**-runque** *queue*] [**-runroot** *directory*] [**-tmpdir** *directory*] [**-usessh**] [**-walltime** *time*]

DESCRIPTION

wind is a Bourne shell script used to run Wind-US, a computational platform for numerically solving various sets of equations governing physical phenomena. Currently, the code supports the solution of the Euler and Navier-Stokes equations of fluid mechanics, along with supporting equation sets governing turbulent and chemically reacting flows. See the *Wind-US User's Guide* for detailed information on the operation and use of Wind-US.

Internally, the *wind* script invokes other scripts, and creates on the fly a *job file* (with the suffix *.job*), which is the actual script submitted to the queue specified by the user.

OPTIONS

-batch Run in "batch" mode, with all necessary input specified via command-line options. The user must specify the Wind-US executable to be run using the **-program** option; all the input/output file names using the **-dat**, **-list**, **-grid**, and **-flow** options; the system run queue using the **-runque** option. The user must also specify either the **-runinplace** option, or the directory to run in using the **-runroot** option. In addition, if a multi-processing control (*.mpc*) file exists, either the **-parallel** or **-noparallel** option must be specified. And, if an *.mpc* file exists and MPI message passing is being used, the number of zones must be specified using the **-nzones** option. If any of these items are missing, an error message will be displayed and execution will stop.

-begtime *time* The beginning time for a standard Unix *at/batch* job (i.e., when using **-runque** AT_QUE).

-binroot *directory* Root location of the Wind-US executable on the system on which it will be running.

-cfdrootrem *directory* The "CFDROOT" directory on the system on which the Wind-US executable will be running. The default is the same as the "CFDROOT" directory on the local machine.

-dat *datfile* The Wind-US input data (*.dat*) file, entered without the extension (e.g., *wing*, not *wing.dat*).

-debug Run Wind-US in debug mode, using the debug package specified by the **-debugger** option. The job will automatically be run interactively, and the **-runinplace** option will be set.

-debugger *debugger* Set the debug package to be used when running in debug mode. The default depends on the computer system being used.

-endtime *time* Ending time for a Unix *at/batch* job, or time to run in seconds for a job running under the basic QSUB, PBS, or LSF queueing system. For the PBS and LSF queueing systems this is the total time for the entire job, minus some length of time for termination processing (i.e., updating the flow (*.cfl*) file, terminating worker processes, etc.) Also see the **-walltime** option.

-flow *cflfile* The Wind-US flow (*.cfl*) output file, entered without the extension (e.g., *wing*, not *wing.cfl*). If the file exists, the solution will restart using the conditions in the file as initial conditions.

-g When specified as the first option, use the *Tcl/Tk* interactive GUI to specify input parameters, ignoring any other options. If **-g** is not the first option specified, it is ignored.

-grid *cgdfile* The Wind-US grid (*.cgd*) input file, entered without the extension (e.g., *wing*, not *wing.cgd*).

-grpcharge *number* Group charge number for the job, used for NAS systems.

-help Display the list of command-line options, and quit, ignoring any other options.

-list *lisfile* The Wind-US list output (*.lis*) file, entered without the extension (e.g., *wing*, not *wing.lis*). Set the parameter *lisfile* to "screen" to display the list output file at the terminal.

-memory *number* Amount of run-time memory to request for a job running under the PBS (in megabytes) or LSF (in kilobytes) batch system.

-mp Run using a multi-processor machine (i.e., a single machine with multiple processors, like the CRAY or SGI Origin-2000), using either PVM or MPI message passing.

-mpmode *mode*
Message passing mode: either PVM or MPI. MPI may only be used on multi-processor systems. Note that the pre-compiled executables available through IVMS were built without MPI message passing. To use **-mpmode MPI**, MPI must be pre-installed on your system (unlike PVM, MPI is not distributed with Wind-US), and you'll need an executable that includes links to the MPI library. See the section "Installing the Build Distribution" in the *Wind-US Installation Guide* for instructions on creating the executable. The default message passing mode is PVM.

-ncpu *number*
Number of CPUs to request for a job running under the PBS or LSF batch system.

-nice_val *number*
The "nice" value (a number from 1 to 20) to use with the Unix *nice* command. Larger values cause the job to run at a lower CPU scheduling priority to lessen the impact on other jobs on the system. For interactive jobs (**-runque** REAL), the value is automatically set to 2. For jobs run in parallel mode, the master task, and worker tasks being run on the same system as the master, automatically run at top priority (i.e., without using *nice*).

-nobg
Jobs in the interactive queue normally run in the foreground if the output is being displayed on the screen, and in the background if the output is being sent to the *.lis* file. This option specifies that the interactive job is to be run in the foreground, even if the output is being sent to the *.lis* file.

-(no)parallel
Run in parallel mode (or serial mode if **-noparallel** is specified). For interactive and *at/batch* jobs, parallel mode requires a multiprocessing control (*.mpc*) file. If this option is not specified, and an *.mpc* file exists, the user will be asked if parallel mode should be used.

-not_nice
Run without using the Unix *nice* command.

-nzones *number*
Number of zones, used in MPI message passing mode on multi-processor systems.

-program *windname*
The name of the Wind-US executable to be used.

-queue_name *name*
The name of the specific queue in which the job is to run. The form of the *name* parameter depends on the queueing system being used, as specified using the **-runque** option.

-remoterun
Bypass some of the built-in error checking for valid path names preventing error messages when running on a remote system. The "CFD-ROOT" directory on the remote machine should be specified using the **-cfdrootrem** option, and the directory to run in should be specified using the **-runroot** option.

-runinplace
Run in place, i.e., in the directory in which the *wind* script was invoked. The default is to run in a remote directory.

-runque *queue*
Queueing system in which the Wind-US executable is to run. The parameter *queue* must be "REAL" for a real-time interactive job; "AT_QUE" to run using a Unix *at* or *batch* queue; "QSUB_QUE" to

run in a basic QSUB queue; "QSUB_PBS_QUE" to run in a QSUB queue using the PBS batch system; or "BSUB_QUE" to run in a BSUB queue using the LSF batch system.

-runroot *directory* — Root directory under which the Wind-US executable is to be run. The full name will be *directory/userid/basename.scr*, where *userid* is your userid and *basename* is the base name of your *.dat* file. The default *directory*, if neither **-runroot** or **-runinplace** is specified, is */tmp*.

-tmpdir *directory* — The directory for storing temporary files during a Wind-US run. The default is the directory specified using the **-runroot** option when running in a remote system, and the current directory when using the **-runinplace** option.

-usessh — Use *ssh* remote shell/copy commands when copying files between the master and workers when running on a cluster. Note that when *ssh* is being used, in addition to using the `-usessh` option the environment variable `PVM_RSH` must be set appropriately, and password-less communication must be allowed between the master and workers. See Section 9.3.2 for details.

-walltime *time* — Total wall clock time in seconds for a job running under the PBS or LSF queueing system. This includes the length of time for termination processing (i.e., updating the flow (*.cfl*) file, terminating worker processes, etc.) Also see the **-endtime** option.

NOTES

Please send documentation suggestions/corrections to `towne@grc.nasa.gov`. Questions concerning Wind-US itself or the NPARC Alliance should be sent to `nparc-support@info.arnold.af.mil`

8.2 *wind_post* — Perform Post-Processing

At the end of a non-debug job that completes successfully, if a script named *wind_post* exists in the current directory, and if the job is not being run interactively, the *wind_post* script is invoked, as follows.

`wind_post` *datname lisname cgdname cflname iter run_command*

The six arguments are defined as:

Argument	Definition
datname	The base name (i.e., without the three-letter extension) of the input data (*.dat*) and job files
lisname	The base name of the list output (*.lis*) file
cgdname	The base name of the grid (*.cgd*) file. (If CGNS files are being used, note that this is the base name of the file itself, not the name of the `CGNSBase_t` node in the file.)
cflname	The base name of the flow (*.cfl*) file
iter	The "job iteration" number. This is a count of the number of jobs, not time step iterations. It is initialized to zero, and incremented by one before each invocation of *wind_post*. Note that the value of *iter* is not saved between runs. The next invocation of the top-level *wind* script will re-initialize the value to zero.
run_command	The command used to submit the job

The *wind_post* script itself must be supplied by the user. Users with some experience in writing shell scripts may use this feature to automatically post-process results at the end of a job, or to save and/or process interim results from a lengthy calculation and submit a new job.[18]

An example *wind_post* Bourne shell script called *wind_post.sh* is supplied with the Wind-US application distribution in the directory *wind/bin*. (There's also an example C shell version called *wind_post.csh*.) The example script resubmits the job with a different input file for each job iteration. It looks for an input data file named *datname.dat.nextiter*, where *datname* is the base name of the *.dat* file and *nextiter* is the *next* job iteration number (i.e., one more that the value of the input argument *iter*). The new input data file, if it exists, is *copied over* the original input data file and the job file is resubmitted.

A typical method for using this capability would be to create files named, for example, *test.dat.1*, *test.dat.2*, *test.dat.3*, etc. Then, copy *test.dat.1* to *test.dat* and submit the job as usual. By keeping the initial input file in *test.dat.1* and copying it to *test.dat*, the original initial input file is preserved.

After the initial job completes, *wind_post* will be called with *iter* = 1. The *next* job iteration number is thus 2. The file *test.dat.2* will be copied into *test.dat*, and the job will be resubmitted, restarting Wind-US where it left off. If the file *test.dat.nextiter* doesn't exist, all the input data files have been used. The job file is then removed, and the run ends.

Note the distinction between a *run* and a *job*, and the value of the job iteration number. By *run*, we mean here a single invocation by the user of the *wind* script. Within that run, multiple *jobs* may be submitted using the *wind_post* feature, each with a different, automatically-incremented job iteration number. As noted above, the job iteration number is not saved between runs. The next time the *wind* script is invoked, starting a new run, the job iteration number will be re-initialized to zero. If it's necessary to save the value between runs, the user-supplied *wind_post* script should save it to a file, to be read during the next run.

The example *wind_post* script does not do any post-processing, but that can easily be added. For example, CFPOST could be run, with input redirected from a command file, to create plot files or reports. Or, an interim flow (*.cfl*) file could be saved by copying it into a file with the *iter* variable as part of the file name.

[18] Note that a similar capability may be invoked using the `SPAWN` keyword in Wind-US's input data file.

8.3 *windver* — Get Wind-US Version Number

The alpha version of Wind-US, and to a lesser extent the beta version, change quite frequently. Even the released production version is sometimes modified, as a result of bug fixes. Changes are summarized in the "Source History" file, accessed through the Internet Version Management System (IVMS).

The *windver* script may be used to get the complete version number of a Wind-US executable, and its supporting libraries. For example,

```
% windver
Versions in ./SGIMP6.5/R12000/bin

                 Select the desired version

  0: Exit wind
  1: alpha version
  2: Version 2.0
  3: Version 3.0
  4: Version 4.0
  5: Version 5.0

Enter number or name of executable.......[5]: 5
 WIND   - Version 5.193 (Last changed 2002/11/05 17:53:28)
 LIBCFD - Version 2.142 (Last changed 2002/10/14 17:27:00)
 LIBADF - Version 2.0.14.1 (Last changed 2002/07/08 17:21:40)
 PVM    - Version 3.4.3
```

windver lists the various Wind-US executables available, and prompts the user to select one of them. It then prints the complete version number, plus the date it was created, for Wind-US, the CFD library (common file processing routines, system-dependent routines, and utility routines), the ADF library (ADF routines from the CGNS project), and the PVM library (PVM routines used for parallel processing). In the above example, WIND Version 5.0 is actually Version 5.193, created on Nov 5, 2002.

By default, *windver* looks for the Wind-US executables in the directory specified by the environment variable `WIND_BINROOT`. If there is no environment variable of that name, *windver* will look in `CFDROOT`. The user may also specify the root location of the Wind-US executable using the option *-binroot*. I.e., invoking *windver* as

```
windver -binroot /usr/local/wind/wind
```

will tell *windver* that the executables are located in the appropriate directories (i.e., in subdirectories corresponding to the `SYSTEM` and `SYSTEM_CPU` environment variables) below */usr/local/wind/wind*.

8.4 *windrun* — Quick Wind-US run

The *windrun* script may be used to quickly set up and start a Wind-US run. The run will be in interactive mode, with the output sent to a *.lis* file. The various options to the script are described below in the form of a Unix-style man page.

NAME

windrun — A quick way to start a Wind-US run

SYNOPSIS

windrun *casename* [**-dev** | **-cfd**] [*windname*] [**-serial** | **-parallel**] [**-new** | **-restart**] [**-runlocal** | **-runtmp**] [**-help**]

DESCRIPTION

windrun is a Bourne shell script used to quickly set up and run Wind-US. Internally *windrun* invokes the *wind* script with the options *-nobg* and *-runque REAL*, and other options determined by the *windrun* input options.

OPTIONS

casename — The prefix for the Wind-US input/output files. All files must have the same prefix (e.g., *case1.cgd*, *case1.cfl*, etc.)

-dev | -cfd — Specifies where to look for the Wind-US executable. If **-dev** is specified, look under the directory defined by the `WIND_DEV` environment variable. If **-cfd** is specified, look under the directory defined by the `CFDROOT` environment variable. The default is to look under the directory defined by the `WIND_DEV` environment variable if the `WIND_DEV` environment variable exists, and under the directory defined by the `CFDROOT` environment variable if the `WIND_DEV` environment variable does not exist.

windname — The name (without the *.exe* extension) of the Wind-US executable to be used (e.g., *windalpha*, not *windalpha.exe*).

-serial | -parallel — If **-serial** is specified, run in serial mode. If **-parallel** is specified, run in parallel mode *on a multiprocessor system* (i.e., using the *-mp* option to the *wind* script), if an *.mpc* file is present. The default is to run in serial mode.

-new | -restart — If **-new** is specified, run a new case from scratch. Any existing *.cfl*, *.tda*, *.cth*, *.lis*, *.job*, *.cge*, and *.cft* files with the prefix *casename*, and any *memdebug.lis* file, in the current directory will be erased before starting the Wind-US run. If **-restart** is specified, start from the the existing solution, if one exists. The default is to run a new case from scratch.

-runlocal | -runtmp — If **-runlocal** is specified, use the *-runinplace* option to the *wind* script to run in the current directory. If **-runtmp** is specified, use the options *-remoterun -runroot $TMPDIR* to run in a temporary directory below the location specified by the `TMPDIR` environment variable. The default is to run in the current directory.

-help — Display a summary on using *windrun*.

8.5 *windmp* — Run on Multi-Processor

The *windmp* script may be used as a shortcut when running Wind-US on a multi-processor machine (i.e., a single machine with multiple processors, like the CRAY or SGI Origin-2000). It simply invokes the *wind* script with the options *-mp*, *-runinplace*, and *-not_nice*.

8.6 *runtest, runtestsuite* — Run Wind-US Test Case(s)

runtest is a utility for running Wind-US test cases. *runtestsuite* is a wrapper for *runtest* that may be used to automate the running of a series of test cases. The various options to both scripts are described below in the form of Unix-style man pages.

The *runtest* Man Page

NAME

runtest — Run Wind-US test cases

SYNOPSIS

runtest *basedir casename* [**-dev** | **-cfd**] [*windname*] [**-serial** | **-parallel**] [**-runlocal** | **-runtmp**] [**-baseline**] [**-help**]

DESCRIPTION

runtest is a Bourne shell script that may be used to run Wind-US test cases. The base name of the case to be run is given by the specified *casename*. *runtest* will look for *casename.dat* and *casename.cgd* input files in the current directory. In addition, *runtest* will recursively descend into any sub-directories and look for input files named *subdir.dat* and *subdir.cgd*, where *subdir* is the sub-directory name.

For example, you could set up a test case named *case1*, with input files *case1.dat* and *case1.cgd.* In the directory containing these files, you could have sub-directories named (say) *run1*, *run2*, etc., containing variations (e.g., different input options) on the original case. *runtest* will *cd* into the sub-directory *run1*, and look for input files named *run1.dat* and *run1.cgd.* Similarly for the sub-directory *run2*, etc. All such cases that are found will be run, in the directory containing the input files.

If a file named *casename.ic.cfl* (or *subdir.ic.cfl* if in a sub-directory, as described above) exists in the run directory, it will be copied as the file *casename.cfl* (or *subdir.cfl*) and used as initial conditions. Otherwise, a new case will be run from scratch. In either situation, any existing output files will be overwritten.

If multiple *.dat* files are found named *casename.1.dat*, *casename.2.dat*, etc. (or *subdir.1.dat*, etc.), multiple runs will be made using the successive *.dat* files to restart the solution.

If the specified case has been run previously, any convergence measures stored in the *.lis* file (i.e., residuals, integrated flow properties, etc.) will be compared with the values from the existing baseline results using *diff*, and the output will be written to the file *basedir/test.log.* In addition, if a file named *delta.com* exists in the directory with the Wind-US input files, it's assumed to contain CFPOST commands. CFPOST is run, with its standard input redirected from *delta.com*, and its standard output appended to the file *basedir/test.log.*

The *-baseline* option may be used to replace an existing baseline solution with the current one, bypassing the comparison of results.

OPTIONS

basedir	The directory where the log file of the tests is to reside.
casename	The prefix for the Wind-US input/output files. All files must have the same prefix (e.g., *case1.cgd*, *case1.cfl*, etc.)
-dev | **-cfd**	Specifies where to look for the Wind-US executable. If **-dev** is specified, look under the directory defined by the `WIND_DEV` environment

variable. If **-cfd** is specified, look under the directory defined by the `CFDROOT` environment variable. The default is to look under the directory defined by the `WIND_DEV` environment variable if the `WIND_DEV` environment variable exists, and under the directory defined by the `CFDROOT` environment variable if the `WIND_DEV` environment variable does not exist.

windname The name (without the *.exe* extension) of the Wind-US executable to be used (e.g., *windalpha*, not *windalpha.exe*). If no name is specified, the default Wind-US version will be used.

-serial | -parallel If **-serial** is specified, run in serial mode. If **-parallel** is specified, run in parallel mode *on a multiprocessor system* (i.e., using the *-mp* option to the *wind* script), if an *.mpc* file is present. The default is to run in serial mode.

-runlocal | -runtmp If **-runlocal** is specified, use the *-runinplace* option to the *wind* script to run in the directory where the input files are found. If **-runtmp** is specified, use the options *-remoterun -runroot $TMPDIR* to run in a temporary directory below the location specified by the `TMPDIR` environment variable. The default is to run in the current directory.

-baseline Replace the saved baseline solution, used for comparison with results from future runs, with the current solution.

-help Display a summary on using *runtest*.

The *runtestsuite* Man Page

NAME

runtestsuite — Run a series of Wind-US test cases

SYNOPSIS

runtestsuite [**-dev** | **-cfd**] [*windname*] [**-serial** | **-parallel**] [**-baseline**] [**-help**]

DESCRIPTION

runtestsuite is a wrapper for the script *runtest* that may be used to automate the running of a series of test cases. It assumes that the cases to be run are stored in subdirectories of the current directory, with the subdirectory names the same as the case names (i.e., the subdirectory names are used for the *casename* argument when invoking the *runtest* script).

OPTIONS

-dev | -cfd Specifies where to look for the Wind-US executable. If **-dev** is specified, look under the directory defined by the `WIND_DEV` environment variable. If **-cfd** is specified, look under the directory defined by the `CFDROOT` environment variable. The default is to look under the directory defined by the `WIND_DEV` environment variable if the `WIND_DEV` environment variable exists, and under the directory defined by the `CFDROOT` environment variable if the `WIND_DEV` environment variable does not exist.

windname The name (without the *.exe* extension) of the Wind-US executable to be used (e.g., *windalpha*, not *windalpha.exe*). If no name is specified, the default Wind-US version will be used.

-serial | -parallel If **-serial** is specified, run in serial mode. If **-parallel** is specified, run in parallel mode *on a multiprocessor system* (i.e., using the *-mp* option to the *wind* script), if an *.mpc* file is present. The default is to run in serial mode.

-baseline Replace the saved baseline solutions for each case, used for comparison with results from future runs, with the current solutions.

-help Display a summary on using *runtestsuite*.

9 Parallel Processing

The time required to compute a solution can be reduced dramatically by using the parallel processing capability of Wind-US, with multiple zones being solved simultaneously. Jobs may be run in parallel mode on a multi-processor system (i.e., a single system with multiple CPUs), or using a collection or cluster of separate, possibly heterogeneous, networked systems, with or without NFS-mounted home directories. Either PVM or MPI message passing may be used on multi-processor systems; only PVM is supported when running on a cluster of networked systems.

Running parallel jobs with Wind-US is remarkably simple. The only user requirement, beyond some initial system and account setup needed for communication, is the creation of a file listing the systems and/or number of processes to be used. The scripts used to start Wind-US automatically take care of copying the necessary files and executables between the systems being used, starting and stopping the message passing software, and cleaning up at the end of the run.

9.1 Terminology

When operating in parallel processing mode, the CPU on which the job originates is called the *master*. All other CPUs are called *workers*. Wind-US distributes grid zones to participating workers. Each zone is solved in parallel with other zones on other workers. Boundary information is exchanged at the end of each cycle to propagate information throughout the computational domain. There may be fewer workers than zones to be computed, in which case, a worker will be assigned another zone when it finishes its current assignment. The user specifies the names of the participating workers via the *multi-processing control (.mpc) file*, described in Section 9.6.

9.2 Parallel-Capable Executables

At the time a Wind-US executable is built, it's linked with the appropriate message passing libraries (i.e., PVM, MPI, or both) that are required for parallel operation. The Wind-US software distributed by the NPARC Alliance includes PVM, but does not include MPI. If MPI is to be used, the MPI libraries must be pre-installed on the multi-processor system being used.

The makefiles used to build the Wind-US executable include switches that specify the message passing software to be used. The default is PVM, and the executables available on IVMS are built for PVM only. If MPI is to be used, an executable must be built from the build distribution, with the appropriate makefile switches set. See the *Wind-US Installation Guide* for details.

If Wind-US will be run in parallel mode on a collection of heterogeneous networked systems, executables must be available for each of the system and CPU types that will be used, and stored on the master. The appropriate Wind-US and PVM executables will automatically be copied from the master to the workers at the start of the run, and removed from the workers when the run finishes. Details on the directory structure required for the executables on the master are presented in Section 9.4.

The run scripts used with Wind-US are designed to use the PVM executables that are part of the Wind-US distribution. If PVM happens to be pre-installed on the system(s) being used, some PVM-related environment variables may already be defined, such as `PVM_ROOT` or `PVM_HOME`. (The environment variables may be listed by issuing the command *setenv*, assuming the C shell or one of its variants is being used as the interactive shell.) In some cases, these have been found to conflict with the execution of Wind-US with its own version of PVM. In this case, the PVM-related environment variables should be unset before starting Wind-US. If the pre-installed version of PVM isn't needed for running other applications, a simple way to do this is to add a line like

```
unsetenv PVM_ROOT
```

in your shell startup file (i.e., *.chsrc* for the C shell).

9.3 Remote Shell Commands

To run in parallel mode using a cluster of separate networked systems, the user must of course have a valid account on the master and each worker system. The user name on the master and all workers must be the same.

In addition, the master must be allowed to communicate with each worker, and vice versa, using remote shell commands, and without entering a password. By "remote shell commands" we mean either *rsh* (*remsh* on HP and Cray systems) and *rcp*, or *ssh* and *scp*.[19] If TCPD access control is installed on the system, which remote shell commands are allowed is normally controlled at the system level by information in the files */etc/hosts.allow* and */etc/hosts.deny*.

9.3.1 *rsh/rcp*

To allow *rsh* and *rcp* to be used without entering a password, the host name of the master system must be in the file *.rhosts* in the user's home directory on the worker system, or in the system file */etc/hosts.equiv* on the worker system, and vice versa. Note that this is required even if the master and worker are the same system. I.e., if the master is also being used as a worker, that system's name must be listed in the *.rhosts* or */etc/hosts.equiv* file.

The *.rhosts* file is a text file containing a list of system names, and the userids on each of those systems, that are allowed to access the current host via *rsh* and *rcp*. The file should have its permissions set to `rw-----`, so issue the following command after creating the file.

```
chmod 600 .rhosts
```

Once the *.rhosts* file has been created, it may be tested by issuing the following command from the system where the job will be submitted.

```
rsh worker-name ls -l
```

Things are functioning properly if the directory listing appears. More information about *.rhosts* files may be found by entering `man rhosts` on most Unix systems.

To tell PVM to use *rsh*, on the master and on each worker you need to set the environment variable `PVM_RSH` equal to the full path name of the *rsh* executable. You'll need to check for the location of *rsh* on your particular system(s). Using "`whereis rsh`" may help. This should be done in your shell start-up file on each system, so that it's defined in all new shells. The name of the shell start-up file, and the format used to specify the environment variable, depends on the shell being used.

As an example, if the *rsh* executable is in */usr/bin*, *tcsh* users would add the following to their *.tcshrc* file.

[19] Note that *rsh* and *rcp* are considered insecure, and many organizations, if not most, now require use of *ssh* and *scp*.

```
setenv PVM_RSH /usr/bin/rsh
```

Similarly, *bash* users would add the following to their *.bashrc* file.

```
PVM_RSH=/usr/bin/rsh
export PVM_RSH
```

9.3.2 *ssh/scp*

Setting up password-less communication using *ssh* and *scp* is a bit more complicated, but only needs to be done once for a given cluster of systems.

When performing the following steps, when you use *ssh* to connect to a new system (i.e., one that you've never connected to using *ssh*, or one whose host key has been changed), you may get a message like

```
The authenticity of host 'system_name (133.11.217.42)' can't be established.
RSA key fingerprint is ec:73:17:40:8d:c0:b5:96:76:27:6b:ce:f4:f9:96:73.
Are you sure you want to continue connecting (yes/no)?
```

If so, respond with "yes" (without the quotes). This will add the host key for *system_name* in your *.ssh/known_hosts* file.

1. First, on the master, create private and public authentication keys by doing

   ```
   ssh-keygen -t rsa
   ```

   The option `-t rsa` means use RSA authentication. If your site uses DSA authentication, you should use the option `-t dsa`. Use the defaults (i.e., just hit Enter) when prompted for a file name and passphrase (i.e., use no passphrase, in order to allow password-less ssh connections).

   This creates, in your */.ssh* directory, the files *id_rsa*, containing your private authentication key, and *id_rsa.pub*, containing your public authentication key. Make sure the *id_rsa* file is only readable by you. I.e., in the *.ssh* directory, doing "`ls -l id_rsa`" should give something like:

   ```
   -rw-------  1 userid userid  883 Jun 23 09:12 id_rsa
   ```

   If it doesn't, do "`chmod 600 id_rsa`".

2. Still on the master, add the public authentication key to the file *.ssh/authorized_keys* in your */.ssh* directory by doing:

   ```
   cd .ssh
   cat id_rsa.pub >> authorized_keys
   ```

3. If your workstation cluster has NFS-mounted home directories (i.e., your home directory physically resides on one node, and is NFS-mounted, or "shared", with the other nodes), do the following.

   - For each node in the cluster, including the master, do

```
ssh node_name ls
```

where *node_name* is the node name. If you get the "`authenticity of host ... can't be established.`" message described earlier, respond with "yes". This will ensure that each node is listed in your *.ssh/known_hosts* file (or is already in the system-wide *ssh_known_hosts* file).

- In your *.ssh* directory, edit the *authorized_keys* file. There should already be a long line there for the master that was created in step 2, that looks something like

  ```
  ssh-rsa public_key= userid@master
  ```

  where *public_key* is a long string of characters containing your public authentication key, *userid* is your user ID, and *master* is the name of the master node. For each additional node in the cluster, copy this line, and change the name *master* at the end of the line to the name of current node.

4. If the cluster you're using has separate home directories on each system, do the following.

   - From the master, add the master's public authentication key to the file *.ssh/authorized_keys* on each worker. I.e, from the *.ssh* directory on the master, for each worker system do the following. (Here, and in the following instructions, replace "*worker*" with the name of the worker system.)

     ```
     cat id_rsa.pub | ssh worker 'cat >> .ssh/authorized_keys'
     ```

   - Log in to each worker system, and create private and public authentication keys on that system. I.e., from the master you could do the following.

     ```
     ssh worker
     ssh-keygen -t rsa
     cd .ssh
     cat id_rsa.pub >> authorized_keys
     ```

   - On each worker, add that worker's public authentication key to the file *.ssh/authorized_keys* on the master. I.e., from the *.ssh* directory on each worker, do the following (where "*master*" is replaced with the name of the master system).

     ```
     cat id_rsa.pub | ssh master 'cat >> .ssh/authorized_keys'
     ```

You should now be able to use *ssh* (and *scp*) from the master to a worker, and vice versa, without entering a password. To test this, on the master do

```
ssh worker ls -l
```

The contents of your home directory on the worker should be displayed. Similarly, on the worker do

```
ssh master ls -l
```

The contents of your home directory on the master should be displayed.

Note that if the master is also being used as a worker, you must also be able to use *ssh* locally. To test this, on the master do

```
ssh master ls -l
```

To tell PVM to use *ssh*, on the master and on each worker you need to set the environment variable `PVM_RSH` equal to the full path name of the *ssh* executable. You'll need to check for the location of *ssh* on your particular system(s). Using "`whereis ssh`" may help. This should be done in your shell start-up file on each system, so that it's defined in all new shells. The name of the shell start-up file, and the format used to specify the environment variable, depends on the shell being used.

As an example, if the *ssh* executable is in */usr/bin*, *tcsh* users would add the following to their *.tcshrc* file.

```
setenv PVM_RSH /usr/bin/ssh
```

Similarly, *bash* users would add the following to their *.bashrc* file.

```
PVM_RSH=/usr/bin/ssh
export PVM_RSH
```

When running Wind-US, use the `-usessh` option to the `wind` script to specify that the executable and I/O files should be copied between the master and workers using *ssh*. I.e.,

```
wind -usessh
```

9.4 Directory Structure on Master

The run scripts expect to find the Wind-US executable(s) (*Wind-US1.exe*, for Wind-US 1.0) and the PVM executables (*pvm*, *pvmd3*, and *pvmgs*) for particular systems and CPUs in specific locations below the `CFDROOT` directory on the master, corresponding to the values of the `SYSTEM` and `SYSTEM_CPU` environment variables for those systems.[20]

As an example, suppose the master is a 32-bit Linux system with a XEON processor and *glibc* version 2.3 (i.e., `SYSTEM = LINUX32-GLIBC2.3` and `SYSTEM_CPU = XEON`). Further, suppose the workers are a mix of 64-bit Linux systems with XEON processors and *glibc* version 2.3, and 64-bit SGI R14000 and R16000 systems. The directory structure on the master below `CFDROOT` would be:

```
$(CFDROOT)/
   LINUX32-GLIBC2.3/
      XEON/
         bin/
            Wind-US executable(s)
   LINUX64-GLIBC2.3/
      XEON/
         bin/
            Wind-US executable(s)
   SGI64-IRIX6.5/
      R14000/
         bin/
            Wind-US executable(s)
      R16000/
```

[20] `CFDROOT` is an environment variable set at login time, by running the *cfd.login* script in the user's *.login* file. For details see the instructions for installing the application or build distribution in the *Wind-US Installation Guide*.

```
    bin/
      Wind-US executable(s)
bin/
  Run scripts
pvm/
  lib/
    LINUX32-GLIBC2.3/
      XEON/
        PVM executables
    LINUX64-GLIBC2.3/
      XEON/
        PVM executables
    SGI64-IRIX6.5/
      R14000/
        PVM executables
      R16000/
        PVM executables
```

When Wind-US is installed following the instructions in the *Wind-US Installation Guide*, the directory structure shown above is automatically created. Note that symbolic links may be used where appropriate. E.g., if only R14000 executables are available for SGI systems, the directory `$(CFDROOT)/SGI64-IRIX6.5/R16000` may be a symbolic link to `$(CFDROOT)/SGI64-IRIX6.5/R14000`.

9.5 Running Parallel Jobs

As noted earlier, running parallel jobs with Wind-US is remarkably simple. Assuming a parallel-capable executable is available for the system(s) being used, and the user's system and account have been set up as described above, the basic steps are:

1. Split the grid into multiple zones. Ideally, there should be one zone for each processor, and each zone should be the same size, assuming the processors have equal computing power. See Section 9.5.2 for additional details.

2. Create a multi-processing control (*.mpc*) file (see Section 9.6) listing the host names of the systems to be used.

3. Issue the *wind* command in one of the following forms.[21]

   - When running on a cluster of networked systems using *rsh*:

     ```
     wind
     ```

   - When running on a cluster of networked systems using *ssh*:

     ```
     wind -usessh
     ```

   - When running on a multi-processor system using PVM:

     ```
     wind -mp
     ```

   - When running on a multi-processor system using MPI:

[21] The commands shown here are the simplest forms. Additional *wind* script options, described in Section 8.1, may be used as needed.

```
wind -mp -mpmode MPI
```

For each of these, respond with "y" when prompted for whether or not you want to run in multi-processor mode.[22]

More detail on various topics related to running parallel jobs with Wind-US is given in the following sections.

9.5.1 Command Line Options

The following *wind* script options are directly applicable to running Wind-US in parallel mode. See Section 8.1 for all the options.

-parallel Run in parallel mode (or serial mode if **-noparallel** is specified). For interactive and *at/batch* jobs, parallel mode requires a multi-processing control (*.mpc*) file. If this option is not specified, and an *.mpc* file exists, the user will be asked if parallel mode should be used.

-mp Run using a multi-processor machine (i.e., a single machine with multiple processors), using either PVM or MPI message passing.

-mpmode *mode* Message passing mode: either PVM or MPI. MPI may only be used on multi-processor systems. Note that the pre-compiled executables available through IVMS were built without MPI message passing. To use **-mpmode** MPI, MPI must be pre-installed on your system (unlike PVM, MPI is not distributed with Wind-US), and you'll need an executable that includes links to the MPI library. See the section "Installing the Build Distribution" in the *Wind-US Installation Guide* for instructions on creating the executable. The default message passing mode is PVM.

-nzones *number* Number of zones, used in MPI message passing mode on multi-processor systems. If this option is not specified, and MPI message passing is being used, the user will be prompted for the number of zones.

-usessh Use *ssh* remote shell/copy commands when copying files between the master and workers when running on a cluster. Note that when *ssh* is being used, in addition to using the `-usessh` option the environment variable `PVM_RSH` must be set appropriately, and password-less communication must be allowed between the master and workers. See Section 9.3.2 for details.

9.5.2 Zone Size Considerations

Because synchronization takes place at the end of each cycle, total throughput is established by the processor that takes the longest to complete its assigned work. The optimum situation is to have all zones of equal size and have one processor for each zone. This gives maximum throughput and processor utilization, but is generally not achievable. If all zones cannot be close to the same size, a mixture of sizes is preferable. The case to avoid is a configuration with one zone of comparable size to the sum of the remaining zones. In this case, one can achieve at most a factor-of-two performance improvement regardless of the number of processors used. In general, if n is the number of points

[22] The wording of this prompt is unfortunate. It really means "parallel mode", not necessarily on a single multi-processor system as defined earlier.

in the largest zone and N is the total number of points, the maximum possible speed up is N/n (assuming identical processors and similar algorithm specification).

Given a number of processors P with relative speeds p_i (larger p implies faster), and a number of zones N of sizes n_j, the assignment of work is done as follows.

1. Assign the largest zone j to processor 1 and compute $T_1 = n_j/p_1$.
2. Repeat step 1 for the remaining $P - 1$ processors, assigning the largest remaining zone j to processor i and compute $T_i = n_j/p_i$.
3. If any zones remain to be assigned, locate processor i such that T_i is a minimum. Assign the largest remaining zone j to processor i, computing $T_i = T_i + n_j/p_i$.
4. Repeat step 3 for remaining unassigned zones.

Consider adding processors if T for any processor is significantly larger than the others, and that processor has more than one zone assigned.

The list output (*.lis*) file from a run will indicate what zones are assigned to what processor, and will have a report containing the utilization of each processor.

9.5.3 Checkpointing and Fault Tolerance

The flow (*.cfl*) file contains the computed flow field results for all the zones, and is stored on the master. Since in parallel mode the zones are solved on separate processors, it's necessary to periodically update the *.cfl* file on the master. By default, the frequency for doing this is once an hour (wall clock time), but this may be changed using the `checkpoint` directive in the *.mpc* file.

If a worker system fails due to either a system or network failure during the course of a run, the job will restart from the last checkpoint without the failed system. The automatic restart ability will be invoked as many times as necessary during a job until no more systems are available.

9.5.4 Intermediate Processing

At each checkpoint, the existing *.cfl* file is overwritten with the updated flow field. During long-running parallel jobs (or serial jobs, for that matter), it's sometimes desirable to do some intermediate processing, to examine how the solution is evolving, or to save snapshots of the results in an unsteady calculation.

The easiest way to do this is by using the `SPAWN` keyword, which allows user-specified processes to be run at user-specified intervals. Wind-US will temporarily stop while a spawned process is running, and continue when it finishes. One typical use of this capability is to run a user-written shell script that creates intermediate results from information in the *.cfl* file. The description of the `SPAWN` keyword includes an example showing how to save intermediate *.cfl* files for later post-processing.

By default, the *.cfl* file is automatically updated before starting the spawned process. This is in addition to the update of the *.cfl* file that's done at each checkpoint. Thus, if the `SPAWN` keyword is used, you may want to eliminate the normal checkpointing by specifying `checkpoint none` in the *.mpc* file.

9.5.5 Multiple Parallel Jobs

When running in parallel mode on a cluster of workstations, the master system and all worker systems being used by a given user cannot be used by any other parallel job from the same user as long as the first job is active. A different user, however, can have a parallel job running simultaneously on the same systems, assuming that the memory, disk space, etc., are sufficient to support multiple jobs.

There are no restrictions on the number of parallel jobs for a given user on a multi-processor system (i.e., using the **-mp** option to the *wind* script; see Section 8.1), again assuming that the computer resources are available to support multiple jobs.

9.5.6 Stopping a Job

When a parallel Wind-US job finishes, the results files are updated on the master, various temporary files are removed on both the master and workers, and the run ends. If PVM message passing was used, PVM is stopped on the master and on all workers.

The methods for specifying when a parallel Wind-US run should stop are the same as for serial runs.

- The job will automatically end when the number of cycles specified by the user have been completed, or the solution converges.
- For non-interactive jobs, either a stop time or run time (depending on the queueing system being used) may be specified when the job is started using the *wind* script. See Section 8.1 for details.
- An `NDSTOP` file may be created in the Wind-US run directory to stop the job, as described in Section 7.7.

Because parallel jobs are often run during off-shift hours, using systems that are needed for other work during normal hours, scripts are supplied with Wind-US that may be executed by the Unix *cron* process to assure that jobs aren't inadvertantly run beyond a certain time. In the Wind-US distribution, these scripts are in the directory *wind/bin/pvmkill*. Four files are located there:

cronkill This file tells the continuous running job scheduler when to terminate processes. The first two digits on each line are the minute, the third digit is the hour, and following the `*`'s are the days when each of the commands will be executed (Monday = 1). The first command is the "nicest" way to kill the job, with the following two successively harsher. Note that this file must be edited so that output goes to your directory and the paths for the scripts are correct.

pvmclean A script which terminates jobs in a relatively nice fashion.

naskill A script which terminates jobs in a bit harsher fashion.

naspvmkill A script which terminates jobs in the meanest fashion.

To invoke these processes, copy the above scripts to *each* master you're using, edit *cronkill* appropriately, and insert these processes into the crontab on each master by entering[23]

[23] Depending on how your system is configured, use of *crontab* may require root access.

```
crontab cronkill
```

To check if this worked, enter

```
crontab -l
```

which will give a list of all your cron entries.

9.5.7 Multi-Processors vs Clusters

Experience has shown that the differences in the procedures for running on a multi-processor system (i.e., a single system with multiple CPUs), and on a cluster of separate networked systems, can be confusing. The following table is an attempt to summarize the differences.

	Multi-Processor	**Cluster**
Definition	Single system with multiple CPUs	Separate networked systems (with or without NFS-mounted home directories)
Message Passing	PVM or MPI	PVM
Required *wind* Options	`-mp`, `-mpmode MPI` (if MPI is used)	None
Host List in *.mpc* File	One `host` line, with `nproc` > 1	Multiple `host` lines
Multiple Jobs OK?	Yes	No

9.6 Multi-Processing Control File

The multi-processing control file specifies the hosts that will be available as well as some miscellaneous options. If the Wind-US input data file name is *input.dat*, the name of the multi-processing control file must be *input.mpc*. When this file is present, the *wind* script will ask the user if they really want to use multi-processing mode.

Comments may be included in the file with the normal Wind-US comment indicator '`/`', or additionally '`#`'. Blank lines are ignored. Trailing comments are not allowed. The formats of the directives follow.

```
host {localhost | hostname} [nproc n]
```

`host` directives specify the names of the worker systems (given by the *hostname* parameter) that will be used to process zones. In general, there should be one `host` directive for each worker system. If a particular system appears more than once, each occurrence is treated as a unique system and will process assigned zones simultaneously. This is not advisable unless the system has multiple processors and sufficient memory.

The optional parameter `nproc` *n* may be used to specify the number of processes to allow to run in parallel on the specified host. It is equivalent to repeating the `host` directive *n* times.

If no `host` entries appear in the multi-processing control file, the originating system will automatically be selected as the only host. When used on a system with sufficient memory and the `assignment mode dedicated` directive, the normal I/O associated with a single processor solution will be eliminated (except for checkpoints).

The special parameter `localhost` is used when running on a single multi-processing system and the system name is unknown at the time of job submittal, such as for batch systems (like NQE) that can spawn to multiple systems or clusters of servers. Using `localhost` is preferred over not putting in any `host` directives because it assures that the scripts set up Wind-US consistently.

`host` entries should appear in the file in decreasing order of computational power. Wind-US assigns the most computationally intensive zones to the highest entries in the list.

The system that originates the job is not automatically included in the host list. If it is desired to also assign solution tasks to the originating system, it should have a host entry like any other system. For estimating purposes, the master process typically consumes less than one percent of the CPU time on the master host.

`i/o {direct | indirect}`

This directive specifies the type of access that worker systems have to files on the master. The default is `indirect`, which means that workers do not have access to the files on the master, and that file I/O must therefore be done using message passing to/from the master process.

On multi-processor systems, however, `i/o direct` may be used to indicate that the worker processes may access the files directly, bypassing communication through the master process. This significantly reduces communication overhead and increases performance by as much as 10-40%.

There are a couple of things to be aware of when using the `i/o direct` option. First, it should only be used when running on a single multi-processor system, not with workstation clusters. And second, the number of open files per process must be set large enough.

`checkpoint {[every] {`*time*` minutes | `*count*` cycles} | none}`

This directive specifies how often the worker systems transfer their flow field information to the flow file on the master system. In the event of a failure, the solution is automatically restarted from the last checkpoint. Specifying too small a number can result in very high network overhead and low throughput. A large number improves performance but can cause wasted time if a lot of network failures occur. If `checkpoint none` is specified, the flow field information is updated only at the end of the job. The default value is

```
checkpoint every 60 minutes
```

Note that if the `SPAWN` keyword is used in the input data (*.dat*) file, the flow field information is also updated before each spawned process, unless the `NOCHECKPOINT` option is specified.

```
assignment mode {dedicated | shared | transient}
```

`assignment mode` controls how tasks are assigned to target systems. There may be multiple appearances of this directive. They affect subsequent `host` entries up to the next `assignment mode` directive. A description of each mode follows.

`dedicated` Each task (zone) gets a unique Unix process on the target system. If a system must process more than one zone, each will have a separate process, but only one will be allowed to run at a time unless multiple `host` entries are present for the system. This is the default mode and should not be changed unless there is insufficient swap space for the processes assigned to the host.

`shared` Unless a system must process more than one zone, this mode is the same as `dedicated`. If more than one zone must be processed, only one Unix process is allocated and individual zones are swapped to and from local disk on the target system. This mode should be used only if the target system does not have sufficient swap space to contain the zones it needs to process.

`transient` When a task completes, it writes all of its flow information back to the master processor and terminates. A new Unix process is then started for the next cycle. This mode is for future use and should not be specified.

```
route [indirect | direct]
```

Controls how data is routed between the master and worker tasks.

`indirect` All messages go from the task on the local machine to the local PVM daemon, over the network to the remote PVM daemon, which forwards it to the remote task.

`direct` All messages go directly from task to task, bypassing the PVM daemons. This mechanism should be more efficient, but cannot be used when the number of zones is large.

`#LOADLIMIT` *limit*

The Wind-US/PVM initialization script will automatically eliminate workers that are deemed "too busy." A system is defined to be "too busy" when its 15 minute load factor, as reported by the Unix "uptime" command (the last number on the line) is greater than a certain limit (0.60 by default). The purpose of this check is to eliminate hosts that are occupied by hung processes.[24]

The load factor for each worker will be displayed in the list output file at the top with the other messages that occur during the preparation of the workers. The load factor will be displayed as a percent (0.60 corresponds to 60%). Note that the load factors in excess of 100% are possible. A message will also be displayed if the load factor exceeds the allowed threshold.

[24] Note that the load factor is checked only at initialization time. If the system becomes busy during a run . . . well . . . too bad.

Occasionally, there is a problem with the "uptime" command and it reports a high load factor when there is no load on the system. To avoid this problem, the #LOADLIMIT directive[25] may be used to override the default value of 0.60. The parameter *limit* specifies the load limit for all hosts up to the next #LOADLIMIT directive. A #LOADLIMIT directive with no parameters restores the default load limit. This command should only be used when you know that including an overloaded host will not affect your job.

The following example illustrates the use of the #LOADLIMIT directive in the multi-processing control file.

```
# Next statement considers hosts ws1463 and ws1464 loaded
#    only if their load factor exceeds 100%
#loadlimit 100
host ws1463
host ws1464
# The next statement restores the default load limit
#loadlimit
host ws1465
# Use a really high limit for ws1466 - disables the limit check
#loadlimit 9999
host ws1456
```

Another way to modify the default load limit is to set the PVM_LOAD_LIMIT environment variable *before* you submit your job. For example, using the Bourne shell:

```
$ PVM_LOAD_LIMIT=75
$ export PVM_LOAD_LIMIT
$ wind
```

[25] Note that this directive is an exception to the use of # as a comment indicator.

10 Keyword Reference

10.1 Text Conventions

In this manual, keywords are indicated by upper-case words in a fixed-pitch font, `LIKE THIS`. In the actual input file, however, they may be entered as upper or lower case. They may also be abbreviated, but Wind-US does *not* check for uniqueness. Therefore, specifying "`A I`" for arbitrary inflow is not a good idea. In cases where multiple options are available, the default (if one exists) is underlined.

User-specified input parameters are indicated by italics, *like this*. These user-specified parameters are usually numeric values, but may also be other keywords.

Most keywords consist of a single line, containing the keyword and its user-specified input parameters. Other keywords, like `CHEMISTRY`, indicate the start of a keyword block containing several lines, bracketed by starting and ending keywords. Within a keyword block, only individual keywords relevant to that block may be used. Keyword blocks are indicated by the word "block" in parentheses. Some keywords have several options, making them long and complex. These are sometimes split into two (or more) lines for display purposes, with a "\" at the end of the line being continued, but must nevertheless be on a single line in the input data file.

The various keywords and keyword blocks are listed alphabetically, with each one starting a new page. The overall syntax for each keyword or keyword block is shown in a box at the top of the page, with the details following.

In addition, the following documentation conventions are used:

`|`	The "or" symbol; used to separate multiple choices
`[]`	Delimiters surrounding optional entry(s)
`{}`	Delimiters surrounding multiple entries when exactly one of them is required

10.2 Zone Selection

Many of Wind-US's capabilities may be specified on a zone-by-zone basis. Keywords used to enable these capabilities may include a zone selector at the end of the keyword command in the input data file. The keywords for which this type of specification is valid include a *zone_selector* format specifier in their description. The *zone_selector* must be of the following form:

`[ZONE]` *zone-list*

where *zone-list* is of the form:

range1 `[,`*range2* `[,`... *rangen*`]]`

A *range* is of the form:

zonenum	Selects zone *zonenum*
begzone`:`*endzone*	Selects all zones from *begzone* to *endzone*
begzone`:`	Selects all zones from *begzone* to `MAXZONE`, the total number of zones in the grid file

`:`*endzone*	Selects all zones from 1 to *endzone*
`ALL`	Selects all zones

For some keywords that turn on capabilities that may be selected by zone, the *zone_selector* is optional (indicated by the syntax `[`*zone_selector*`]`). In this case, omitting the zone specification defaults to using the capability in all zones. You should therefore change the default selection before changing individual zones, as changing the default will reset any zones which have been individually set earlier in the input file.

Example

To turn off (i.e., perform no iterations) in zones 5, 6, and 7, but still pass the information in these zones to the adjacent zones, and to use 10 iterations per cycle in all other zones, use the following sequence of keywords:

```
ITERATIONS PER CYCLE 10
ITERATIONS PER CYCLE -1 ZONE 5:7
```

Note that reversing the order of the keywords would not work because resetting the default will override the initial selection.

10.3 Keyword Details

The following is a comprehensive, alphabetical list of all keywords that are valid in the Wind-US input data file. Every attempt was made to build keyword inputs from intuitive, English-language words, and to adhere to some general rules of construction for the keyword commands in the data file.

Many of the keywords apply to either structured grids (e.g., `ACTUATOR`) or unstructured grids (e.g., `Q LIMIT`), but not both. For these keywords, the type of grid that the keyword applies to is listed above the box showing the keyword syntax.

Several other keywords apply to both types of grids, but with different options or syntaxes (e.g, `CFL#`). For these keywords, two syntax boxes are shown, again with labels specifying the grid type. In general, the detailed description of these keywords is divided into separate sections for structured and unstructured grids.

The remaining keywords apply to both types of grids. If the keyword syntax box isn't labeled with the words "Structured Grids" or "Unstructured Grids" (e.g., `FREESTREAM`), that keyword applies to both types of grids, with the same options and syntax.

ACCELERATE — Convergence acceleration (block)

Structured Grids

```
ACCELERATE
   ZONE $n$
   [CFLRAMP START $iter_1$ END $iter_2$]
   [SECOND START $iter_1$ END $iter_2$]
   [FOURTH START $iter_1$ END $iter_2$]
ENDACCELERATE
```

Unstructured Grids

```
ACCELERATE
   ZONE $n$
   [CFLRAMP START $iter_1$ END $iter_2$]
ENDACCELERATE
```

The objective of Wind-US's convergence acceleration scheme is to approach the steady state solution more quickly by allowing the use of a large CFL number early in the calculation, adding smoothing to maintain numerical stability. This option should be used in conjunction with the `SMOOTHING` keyword.

Structured Grids

The `ZONE` keyword identifies the zone within which convergence acceleration is to be used. If convergence acceleration is to be used in multiple zones, and/or if different starting and ending iteration values are to be used in different zones, multiple `ZONE` keywords must be specified.

$iter_1$ and $iter_2$ specify starting and ending iteration values for varying the corresponding keyword parameter. If these aren't specified, the following default values are used.

Option	$iter_1$	$iter_2$
`SECOND`	1	150
`FOURTH`	50	500
`CFLRAMP`	50	500

The CFL number will be ramped down linearly from its starting value, specified using the `CFL#` keyword, to 1.0. The `ACCELERATE` keyword does not work when `CFL# MODE 3` (i.e., the time step calculation procedure from OVERFLOW) is used.

The smoothing that is applied depends on the *mode* used with `TEST` option 49, and the input from the `SMOOTHING` and/or `BOUNDARY-DAMP` keywords. For the second-order smoothing,

mode	Second-Order Smoothing
< 2	Smoothing varies with iteration i, as follows:

$i \leq iter_1$	Smoothing applied as determined by the SMOOTHING keyword
$iter_1 < i < iter_2$	Smoothing coefficient decreased linearly to 0
$i \geq iter_2$	No smoothing applied

2	Smoothing varies with iteration i, as follows:

$i \leq iter_1$	Smoothing applied as determined by the SMOOTHING and BOUNDARY-DAMP keywords
$iter_1 < i < iter_2$	Smoothing coefficient decreased linearly to 0
$i \geq iter_2$	No smoothing applied

3	No smoothing applied

And for the fourth-order smoothing,

mode	Second-Order Smoothing
< 2	Smoothing applied as determined by the SMOOTHING keyword
2	Smoothing varies with iteration i, as follows:

$i \leq iter_1$	No smoothing applied
$iter_1 < i < (iter_1 + iter_2)/2$	Smoothing coefficient increased linearly from 0 to value determined by the SMOOTHING and/or BOUNDARY-DAMP keywords
$(iter_1 + iter_2)/2 < i < iter_2$	Smoothing coefficient decreased linearly to 0
$i \geq iter_2$	No smoothing applied

3	Smoothing applied as determined by the SMOOTHING and BOUNDARY-DAMP keywords

Recommended values for the second- and fourth-order smoothing parameters val_1 and val_2 specified with the SMOOTHING keyword, and for the starting CFL number, are:

Dimensions	val_1	val_2	CFL #
2D	0.1	0.03	10–15
3D	0.06	0.01	2.5

Example

In the following example, convergence acceleration is applied in zones 3 and 4. Second-order smoothing is applied between iterations 1 and 200, and fourth-order smoothing is applied between the default values of iterations 50 and 500. The CFL number specified with the CFL# keyword will be used for the first 250 iterations, then ramped down to a value of 1.0 between iterations 250 and 500.

```
SMOOTHING SECOND 0.06 FOURTH 0.01 SMLIMT 0.
ACCELERATE
   ZONE 3
   ZONE 4
   SECOND START 1 END 200
   CFLRAMP START 250 END 500
ENDACCELERATE
TEST 49 2
```

See Also: SMOOTHING, BOUNDARY-DAMP, CFL#, TEST 49

Unstructured Grids

The ZONE keyword identifies the zone within which convergence acceleration is to be used. If convergence acceleration is to be used in multiple zones, and/or if different starting and ending iteration values are to be used in different zones, multiple ZONE keywords must be specified.

$iter_1$ and $iter_2$ specify starting and ending iteration values for varying the CFL number. Just as for structured grids, for unstructured grids the CFL number will be ramped down linearly from its starting value, specified using the CFL# keyword, to 1.0. If the CFLRAMP keyword isn't specified, default values of 50 and 500 are used, for $iter_1$ and $iter_2$.

For unstructured grids, however, no variation in smoothing is done. The smoothing specified with the SMOOTHING keyword is used for all iterations.

See Also: SMOOTHING, CFL#

ACTUATOR | SCREEN — Discontinuous change across a zone boundary (block)

Structured Grids

```
{ACTUATOR | SCREEN}
   ZONE iz1 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
        [SUBSET I range J range K range]
   ZONE iz2 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
        [SUBSET I range J range K range]
   TURNING {CONSERVE {ANGLE | PARALLELU} | \
            ZERO PARALLELU | \
            {SOLIDBODY | VORTEX} val x_c y_c z_c | \
            SPECIFY ANGLE α [ROTATE β]}
   TIP-EFFECT r1 r2 r3 r4
   POWER {{DPS | DPT | DPOWER} val | \
          TURNING | \
          {SOLIDBODY | VORTEX} val x_c y_c z_c}
   EFFICIENCY {ETA val | \
               CLOSS val | \
               VORTEX val | \
               SCREEN {NORMAL | TOTAL} SOLIDITY sol}
{ENDACTUATOR | ENDSCREEN}
```

This keyword enables the user to specify a discontinuous change in properties across a zone boundary or portion of a zone boundary. Examples include actuator disks, engine face models, and screens.

The following restrictions apply:

- This keyword applies to structured grids only.
- The `BOUNDARY TVD FACTOR 0` keyword option should be used for all actuator disk and screen boundaries.
- Screens require zero work (`POWER DPOWER 0.`)
- Only one storage location for center of rotation, the last one encountered is used for all centers.

The various elements of the `ACTUATOR | SCREEN` input block are defined as follows:

```
{ACTUATOR | SCREEN}
```

Defines the beginning of the actuator or screen block.

```
ZONE iz1 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
     [SUBSET I range J range K range]
ZONE iz2 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
     [SUBSET I range J range K range]
```

These two lines define the location of the actuator disk or screen. The relevant zones are given by the values of *iz1* and *iz2*, and the relevant boundaries within zones *iz1* and *iz2* are specified via the `BOUNDARY` keyword parameter.

iz1 Zone to which increments will be added when passing information to *iz2*

iz2 Zone receiving positive increments, increments will be subtracted when passing information back to zone *iz1*

The SUBSET parameter may be used to specify that the change in properties occurs only over a part of the zone boundary. Otherwise, it is assumed that the change occurs over the entire boundary. The *range* parameters define the part of the zone boundary over which the change occurs, and take one of the following forms:

index1 index2 Starting and ending indices in the specified direction. LAST may be used for the last index.

ALL Equivalent to 1 LAST.

The starting and ending indices for the appropriate I, J, or K parameter (depending on the boundary specified) must be the same, and correspond to that boundary. In addition, for two-dimensional cases, the K parameter must be specified as either K 1 1 or K ALL.

```
TURNING {CONSERVE {ANGLE | PARALLELU} | \
        ZERO PARALLELU | \
        {SOLIDBODY | VORTEX} val x_c y_c z_c | \
        SPECIFY ANGLE α [ROTATE β]}
```

Defines the net change in parallel velocity across the zone boundary.

CONSERVE Conserves the net flow angle (ANGLE) or the parallel velocity components (PARALLELU) across the zone boundary. (The ANGLE option is currently not implemented.)

ZERO PARALLELU Sets the parallel components of velocity across the zone boundary to zero

SOLIDBODY Defines a solidbody rotation increment to the parallel velocity, where:

val Rotation rate in radians/second (positive by right hand rule)

x_c, y_c, z_c Center of rotation (must be in the plane, requires the zone boundary to lie in a constant x, y, or z plane) (inches)

VORTEX Defines free vortex flow increment to parallel velocity, where:

val Vortex strength κ (ft^2/sec), where $\kappa = \omega a^2 = \Gamma/2\pi$, and Γ is the circulation, ω is the rotation rate of the solidbody core, and a is the radius of the solidbody core (required to avoid $P = 0$ at axis), $a^2 = \kappa^2\rho/(0.9P_\infty)$ (assumes $P_{min} = 0.1P_\infty$)

x_c, y_c, z_c Center of rotation (inches)

SPECIFY ANGLE Allows the user to specify the flow turning angle.

alpha The flow angle giving the rotation of the *iz2* boundary normal, projected onto the x-y plane, about the z-axis (degrees)

beta An optional rotation of the resulting vector about the y-axis

```
TIP-EFFECT r1 r2 r3 r4
```

Forces increments to go to zero at hub and/or tip to avoid solution discontinuities at the boundaries. A scalar, (0–1) multiplies the turning and power when this option is on. This is required for engine face models (where the wall velocity at the tip must be zero in the diffuser frame of reference). *r1*–*r4* define linear regions ranging from 0 to 1 between *r1* and *r2*, and from 1 to 0 between *r3* and *r4*. *r1*, *r2*, *r3*, and *r4* define the distance from the center of rotation (inches).

This keyword requires that `TURNING SOLIDBODY`, `TURNING VORTEX`, or `POWER SOLIDBODY` be specified.

```
POWER {{DPS | DPT | DPOWER} val | \
       TURNING | \
       {SOLIDBODY | VORTEX} val x_c y_c z_c}
```

Defines the power increment across the zone boundary. Screens require setting the power to zero. i.e., `POWER DPOWER 0.`

`DPS` — *val* specifies the static pressure increment across the actuator boundary (psi). Requires that the efficiency be specified, using `EFFICIENCY ETA`.

`DPT` — *val* specifies the total pressure increment across the actuator boundary (psi). Requires that the efficiency be specified, using `EFFICIENCY ETA`.

`DPOWER` — *val* specifies a (constant) power per unit area increment. (ft-lb/sec-ft^2). (Corresponds to unsteady (rotor) free vortex turning)

$\texttt{DPOWER} = \rho u c_p (T_{t2} - T_{t1})$

`TURNING` — Specifies work corresponding to the net turn across the zone boundary (specified in the `TURNING` element). Assumes all turning is done in an unsteady process (by the rotor), i.e., no stator.

$dW = c_p(T_{t2} - T_{t1}) = \omega r (w_2 - w_1)$

where ω is the rotation rate of the rotor, r is the local radius from the center of the rotor, and w is the local circumferential velocity.

This option requires that `TURNING SOLIDBODY` be specified.

`SOLIDBODY | VORTEX` — Defined as in the `TURNING` element. This defines the turning accomplished by the rotor. The net turning may be altered by another process (e.g., by a stator).

$dW = c_p(T_{t2} - T_{t1}) = \omega r (w_2 - w_1)$

Note: Currently vortex turning (i.e., `POWER VORTEX`) is not allowed. This would correspond to constant work across the rotor. However, currently, the procedure used to eliminate the vacuum at the core (setting $P_{min} = 0.1 P_\infty$) makes the work input independent of the strength of the vortex, so the user could not vary the work input by changing κ.

```
EFFICIENCY {ETA val | \
            CLOSS val | \
            VORTEX val | \
            SCREEN {NORMAL | TOTAL} SOLIDITY sol}
```

Defines the efficiency of the actuator disk or screen.

`ETA` Compressor efficiency, $val = [(P_{t2}/P_{t1})^{(\gamma-1)/\gamma} - 1]/[(T_{t2}/T_{t1}) - 1]$

`CLOSS` Loss coefficient, $val = (P_{t1} - P_{t2})/q$, where $q = \rho U^2/2$ (U based on normal Mach number)

`VORTEX` Free vortex total pressure loss. The value *val* is the maximum value of $(P_{t2} - P_{t1})/P_{tinf}$ (i.e., the loss at the center of the vortex). A linear distribution is assumed from the vortex center to the radius a, where a is determined by the strength value specified using `TURNING VORTEX`, or directly using `TEST 180`.

This option requires that `TURNING VORTEX` be specified.

`SCREEN` Use screen loss relations to define total pressure loss, where

`NORMAL` Use normal component of Mach number

`TOTAL` Use total Mach number. (This option is not currently implemented.)

sol Solidity of screen $= A_b/(A_b + A_o)$, where A_b is the blocked area, and A_o is the open area.

If solidity is specified, the screen loss coefficient associated with the screen model is defined by the solidity correlation of Cornell (1958), unless the optional `CLOSS` value is specified.

The screen model is not intended for use with choked screens, where the screen is significantly limiting the mass flow rate. During the solution start-up phase, it may be necessary to specify a low solidity, then increase it to the desired value to avoid strong choking in transients.

This option requires that the power be zero. i.e., `POWER DPOWER 0.`

```
{ENDACTUATOR | ENDSCREEN}
```

Ends actuator or screen input block

Examples

The following examples illustrate the use of the `ACTUATOR | SCREEN` input block for an engine face and for a screen.

Engine face model

```
ACTUATOR
   ZONE 1 BOUNDARY IMAX
   ZONE 2 BOUNDARY I1
   TURNING SOLIDBODY 240000. 312. 54. 0.
   TIP-EFFECT 5. 5.1 39.8 40.0
   POWER TURNING
   EFFICIENCY ETA 0.85
ENDACTUATOR
BOUNDARY TVD FACTOR 0 ZONE 1 BOUNDARY IMAX
BOUNDARY TVD FACTOR 0 ZONE 2 BOUNDARY I1
```

Screen

```
SCREEN
   ZONE 3 BOUNDARY K1
   ZONE 2 BOUNDARY IMAX
   TURNING ZERO PARALLELU
   POWER DPOWER 0.0
   EFFICIENCY SCREEN NORMAL SOLIDITY 0.1
ENDSCREEN
BOUNDARY TVD FACTOR 0 ZONE 3 BOUNDARY K1
BOUNDARY TVD FACTOR 0 ZONE 2 BOUNDARY IMAX
```

See Also: `BOUNDARY TVD`, `TEST 180`

ARBITRARY INFLOW — Arbitrary inflow (block)

Structured Grids

```
{ARBITRARY INFLOW | DIFFUSER INFLOW}
   [STATIC | TOTAL]
   [HOLD_TOTALS | HOLD_CHARACTERISTICS]
   [DIRECTION {SPECIFIED | NORMAL [TO INFLOW PLANE] | ALONG [GRID LINES]}]
   ZONE n
   [UNIFORM [M P T $\alpha$ $\beta$ [val_k [val_om]]]
      [$sp_1$ $sp_2$ ...$sp_n$]]
   [IJK_RANGE [FROZEN] imin imax jmin jmax kmin kmax M P T $\alpha$ $\beta$ [val_k [val_om]]
      [$sp_1$ $sp_2$ ...$sp_n$]]
   [UNSTEADY var_name freq ampl phase]
   [{VORTEX | SOLIDBODY | ROTATESOLID} $M_n$ P T $\alpha$ $\beta$ xc yc zc \
      {dw1 | dw1 dw2 dw3}]
   [USERSPEC fs bl1 bl2 npts
      y1 M P T $\alpha$ $\beta$
      y2 M P T $\alpha$ $\beta$
      ...
      yn M P T $\alpha$ $\beta$]
   [USERCHEM fs bl1 bl2 npts
      y1 M P T $\alpha$ $\beta$
         $sp_1$ $sp_2$ ...$sp_n$
      y2 M P T $\alpha$ $\beta$
         $sp_1$ $sp_2$ ...$sp_n$
      ...
      yn M P T $\alpha$ $\beta$
         $sp_1$ $sp_2$ ...$sp_n$]
   [USERKE fs bl1 bl2 npts
      y1 M P T $\alpha$ $\beta$ val_k [val_om]
      y2 M P T $\alpha$ $\beta$ val_k [val_om]
      ...
      yn M P T $\alpha$ $\beta$ val_k [val_om]]
   [USERCHEMKE fs bl1 bl2 npts
      y1 M P T $\alpha$ $\beta$
         $sp_1$ $sp_2$ ...$sp_n$ val_k [val_om]
      y2 M P T $\alpha$ $\beta$
         $sp_1$ $sp_2$ ...$sp_n$ val_k [val_om]
      ...
      yn M P T $\alpha$ $\beta$
         $sp_1$ $sp_2$ ...$sp_n$ val_k [val_om]]
[ENDINFLOW]
```

Unstructured Grids

```
{ARBITRARY INFLOW | DIFFUSER INFLOW}
   [STATIC | TOTAL]
   [HOLD_TOTALS]
   ZONE $n$
   [UNIFORM [$M$ $P$ $T$ $\alpha$ $\beta$]]
      [$sp_1$ $sp_2$ $\ldots sp_n$]]
   [USURFACE {[FROZEN] $surface$ $M$ $P$ $T$ $\alpha$ $\beta$ [$sp_1$ $sp_2$ $\ldots sp_n$] | \
              MASS $surface$ $mass$ $area$ $Ttotal$ $\alpha$ $\beta$}]
[ENDINFLOW]
```

Several options are available to set conditions at arbitrary inflow boundaries. The default is uniform inflow (i.e., no boundary layer) at the conditions that are set using the FREESTREAM keyword. Other options are selected by using either of the equivalent keywords ARBITRARY INFLOW or DIFFUSER INFLOW.

The remaining lines select the specific type of inflow data to be provided. Discussion of the input data for each of these options is grouped into sections labeled “Control Functions”, “Condition Specification”, and “Special Capabilities”. These keywords can start in any column. Generally, they should be indented from the ARBITRARY INFLOW keyword to set them apart.

For structured grids, this keyword may also be used to initialize (or reinitialize) the flow conditions within the specified zone, as described in Section 3.6.

Note: The GAS keyword and the CHEMISTRY keyword block, if used, must come before the ARBITRARY INFLOW keyword block in the input data (*.dat*) file.

Structured Grids

Control Functions

```
ENDINFLOW
```

This optional keyword may be used to end the arbitrary inflow definition.

```
STATIC | TOTAL
```

Arbitrary inflow conditions specified after this keyword will be considered as static or total, depending which of these is set. By default, the flag is set to the value from the FREESTREAM keyword.

Note: TOTAL is only valid for an ideal gas.

```
HOLD_TOTALS | HOLD_CHARACTERISTICS
```

HOLD_TOTALS indicates that total temperature and local flow angles are to be held at their specified values. HOLD_TOTALS is only valid for a perfect gas. HOLD_CHARACTERISTICS indicates that characteristic values are to be held constant. The option specified will be applied at all the arbitrary inflow regions in the zone, and will remain in effect for all following ZONE keywords.

The default for structured grids is to hold characteristic values constant.

These keywords only work in conjunction with the UNIFORM, IJK_RANGE, VORTEX, SOLIDBODY, and ROTATESOLID keywords.

The total pressure is always held fixed, whether HOLD_TOTALS is specified or not. Although the Mach number is specified with the UNIFORM and IJK_RANGE keyword parameters, it may be adjusted during the boundary condition treatment.

Note that the HOLD_TOTALS keyword in the ARBITRARY INFLOW keyword block applies to arbitrary inflow boundaries only. See the HOLD keyword for information on holding conditions at freestream boundaries in structured grids with inflow.

Note also that the syntax is slightly different for arbitrary inflow and freestream boundaries. For arbitrary inflow boundaries, HOLD_TOTALS and HOLD_CHARACTERISTICS are used in the ARBITRARY INFLOW keyword block, with an underscore. For freestream boundaries, HOLD TOTALS and HOLD CHARACTERISTICS are used, without an underscore.

```
DIRECTION {SPECIFIED | NORMAL [TO INFLOW PLANE] | ALONG [GRID LINES]}
```

For structured grids, the DIRECTION keyword indicates how the flow angle is to be set at an inflow plane. The options for setting the flow direction are:

SPECIFIED Set the flow at the angles of attack and yaw specified elsewhere in the ARBITRARY INFLOW block. This is the default.

NORMAL Set the flow normal to the inflow plane.

ALONG Set the flow in the direction of the grid lines intersecting the inflow plane.

Specifying DIRECTION NORMAL or DIRECTION ALONG will override any angles of attack or yaw specified with the UNIFORM, IJK_RANGE, VORTEX, SOLIDBODY, and ROTATESOLID keywords. However, if UNIFORM is used without specifying the flow conditions, the angles specified with the FREESTREAM keyword will be used, and the DIRECTION keyword will have no effect. The DIRECTION keyword also does not affect flow angles in profiles specified with the USERSPEC, USERCHEM, USERKE, or USERCHEMKE keywords.

The DIRECTION keyword will not modify the flow angles that are set when ARBITRARY INFLOW is being used to initialize (or reinitialize) flow conditions within a zone.

The DIRECTION option used will remain in effect for all following ZONE keywords.

ZONE *n*

This keyword, which *must* be specified, identifies the zone for which inflow conditions are being set. For example, if zone 2 is an internal jet, conditions other than freestream may be desired at the inflow to zone 2.

Within the ARBITRARY INFLOW keyword block, the ZONE keyword must come *before* any "Condition Specification" keyword for that zone, but *after* any HOLD_TOTALS, HOLD_CHARACTERISTICS, or DIRECTION keyword for that zone. In addition, inflow conditions may only be specified for one zone at a time.

Example

The following ARBITRARY INFLOW block specifies that total conditions are to be held constant at arbitrary inflow surfaces in zones 1 and 2, with $M = 3.5$, $P_T = 251.15$ psi, and $T_T = 1167.9$ °R. In zone 3, characteristic values are to be held constant at arbitrary inflow surfaces, consistent with the flow conditions given with the FREESTREAM keyword.

```
ARBITRARY INFLOW
   TOTAL
   HOLD_TOTALS
      ZONE 1
      UNIFORM 2.5 251.15 1167.9 0.0 0.0
      ZONE 2
      UNIFORM 2.5 251.15 1167.9 0.0 0.0
   HOLD_CHARACTERISTICS
      ZONE 3
      UNIFORM
ENDINFLOW
```

Condition Specification

UNIFORM [M P T α β [*val_k* [*val_om*]]]
   [sp_1 sp_2 $\ldots sp_n$]

This keyword is used to specify uniform flow at arbitrary inflow boundaries, at the flow conditions listed below. If the flow conditions are omitted, those specified with the FREESTREAM keyword are used.

M	Mach number
P	Pressure, psi
T	Temperature, °R
α, β	Angles of attack and yaw, relative to the Cartesian x direction, in degrees
sp_1, sp_2, $\ldots$, sp_n	Species mass fractions. These are required for real gas flows.

Pressure and temperature are static or total, depending on whether STATIC or TOTAL is specified.

For structured grids, when the SST turbulence model is being used (see the TURBULENCE keyword), *val_k* and *val_om* may be used to specify inflow turbulence levels. You may specify either *val_k*, or *val_k* and *val_om*, but not *val_om* by itself. Note that if these values are being specified, the TURBULENCE keyword must come before the ARBITRARY INFLOW keyword block in the input data (*.dat*) file.

The following options are possible:

val_k > 0 The turbulent kinetic energy k and the specific dissipation rate ω are specified directly, with

$$k = val\_k \ (\mathrm{ft}^2/\mathrm{sec}^2)$$
$$\omega = val\_om \ (1/\mathrm{sec})$$

The turbulent viscosity ν_t is then equal to k/ω.

val_k < 0 — The turbulence intensity is set equal to $|val\_k|$, expressed as a percentage of the inflow velocity U, where U is computed from the specified values of M and T. Thus, the turbulent kinetic energy is computed as

$$k = 1.5(0.01\,|val\_k|\,U)^2$$

The turbulent viscosity ν_t is automatically set equal to $0.001\nu_l$, where ν_l is the laminar viscosity, and the specific dissipation rate is computed as $\omega = k/\nu_t$.

val_om < 0 — The specific dissipation rate ω is set equal to *val_om* percent of U/L_{ref}, where U is computed from the specified values of M and T, and L_{ref} is the reference length from the grid (*.cgd*) file. Thus

$$\omega = 0.01\,|val\_om|\,\frac{U}{L_{ref}}$$

The turbulent viscosity ν_t is set to the same percentage of the laminar viscosity.

$$\nu_t = 0.01\,|val\_om|\,\nu_l$$

The turbulent kinetic energy is then computed as $k = \omega\nu_t$.

If inflow turbulence levels are not specified using one of the above options, or if $val\_k = 0$, default values are computed from

$$\begin{aligned} \omega &= 10U/L_{ref} \\ \nu_t &= 0.001\nu_l \\ k &= \omega\nu_t \end{aligned}$$

Note that

- If $val\_k > 0$, a positive value must be specified for *val_om*.
- If $val\_k \leq 0$, *val_om* should not be specified.
- If $val\_om < 0$, a value must also be specified for *val_k*, but it is ignored.

Example

```
ARBITRARY INFLOW
   UNIFORM 1.1 100. 900. 10. 0.
ENDINFLOW
```

`IJK_RANGE [FROZEN]` *imin imax jmin jmax kmin kmax M P T* α β `[`*val_k* `[`*val_om*`]]`
   `[`sp_1 sp_2 $\ldots sp_n$`]`

For structured grids, this keyword allows specification of inflow conditions over an arbitrary range of i, j, and k indices on any computational boundary plane. The user specifies the minimum and maximum i, j, and k indices which describe the region, followed by the flow conditions to be applied, as follows:

imin, imax — Minimum and maximum i indices bounding the region

jmin, jmax	Minimum and maximum j indices bounding the region
kmin, kmax	Minimum and maximum k indices bounding the region
M	Mach number
P	Pressure, psi
T	Temperature, °R
α, β	Angles of attack and yaw, relative to the Cartesian x direction, in degrees
sp_1, sp_2, $\ldots$, sp_n	Species mass fractions. These are required for real gas flows.

Pressure and temperature are static or total, depending on whether `STATIC` or `TOTAL` is specified. There are no defaults for the index ranges.

The `FROZEN` option may be specified to freeze the inflow conditions over the indicated index range at their current values. Note that for a restart case (i.e., when a *.cfl* file already exists), the "current values" are those in the *.cfl* file, not those specified with the `IJK_RANGE` keyword. For an initial run (i.e., when a *.cfl* file does not exist), the flow conditions will be frozen at the conditions specified with the `IJK_RANGE` keyword.

If the SST turbulence model is being used (see the `TURBULENCE` keyword), *val_k* and *val_om* may be used to specify inflow turbulence levels. The various options are described above under the `UNIFORM` keyword.

Up to 500 `IJK_RANGE` keywords may be specified. This is useful when specifying a boundary layer profile at an inflow boundary, or along solid walls during the flowfield initialization process, as described in Section 3.6 starting on p. 36.

`UNSTEADY` *var_name freq ampl phase*

For structured grids, this keyword allows the user to specify unsteady arbitrary inflow conditions. It must be used with (and follow) the `IJK_RANGE` keyword. Up to three different perturbations to the inflow conditions may be specified and will be superimposed to create unsteadiness centered about the conditions given with the `IJK_RANGE` keyword.

var_name	One of the keywords `MACH`, `PRESSURE`, `TEMPERATURE`, `ALPHA`, `BETA`, or `VELOCITY`
freq	Frequency of the perturbation in Hertz
ampl	Amplitude of the perturbation in appropriate variable units
phase	Phase angle of the perturbation in degrees

Note that you may specify multiple, independent pairs of `IJK_RANGE` and `UNSTEADY` keywords.

`{VORTEX | SOLIDBODY | ROTATESOLID}` M_n P T α β *xc yc zc* `{`*dw1* `|` *dw1 dw2 dw3*`}`

For structured grids, these keywords may be used to specify uniform inflow conditions with free-vortex or solid-body rotation superimposed. Solid-body rotation may be specified on any arbitrary inflow boundary. For free-vortex rotation, however, the arbitrary inflow boundary must be a constant x, y, or z plane, and the center of rotation must lie on that plane.

M_n	Normal component of Mach number
P	Pressure, psi
T	Temperature, °R
α, β	Average angles of attack and yaw, relative to the Cartesian x direction, in degrees
xc, yc, zc	Center of rotation in physical coordinates

For `VORTEX`,

dw1	Vortex strength. (See the `ACTUATOR` keyword.)

For `SOLIDBODY` and `ROTATESOLID`,

dw1, dw2, dw3	x, y, and z components of the rotation rate vector (radians/sec)

The rotational velocity components are added in such a way that total pressure and total temperature are held constant at the inflow boundary. Thus, the `TOTAL` option should always be used for this mode, since with the `STATIC` option the computed static pressure and temperature at the inflow boundary may differ from the specified values.

For calculations in a rotating reference frame (see the `ROTATE` keyword):

- If the `SOLIDBODY` option is used, the total conditions specified are those in the rotating frame, and are held fixed in that frame. The total conditions in the inertial frame will vary.
- If the `ROTATESOLID` option is used, the total conditions specified are those in the inertial frame, and are held fixed in that frame. The total conditions in the rotating frame will vary. Note that the `ROTATESOLID` option is only valid for calculations in a rotating reference frame.

For both free-vortex and solid-body rotation, the flowfield must already be initialized. (See Section 3.6.) I.e., there must be a pre-existing *.cfl* file. The `VORTEX`, `SOLIDBODY`, and `ROTATESOLID` options cannot be used during a "cold" start.

Special Capabilities

The following arbitrary inflow keywords are only valid for structured grids, and are only applied at the $i = 1$ computational plane.

```
USERSPEC fs bl1 bl2 npts
   y1 M P T α β
   y2 M P T α β
   . . .
   yn M P T α β
```

This option allows the user to specify a 1-D profile normal to the surface, translated through some buttline range, below the vehicle. These conditions will be set last and thus the data will overwrite `UNIFORM` conditions over the range of interest.

fs Fuselage station of the profile (to be checked against the grid $i = 1$ fuselage station)

bl1, bl2 Minimum and maximum buttline over which to translate the profile

npts Number of points defining the profile

y1 – yn Normal distance from the wall

M Mach number

P Pressure, psi

T Temperature, °R

α, β Angles of attack and yaw, relative to the Cartesian x direction, in degrees

The pressure and temperature may be the total or static conditions, depending upon the current setting of the `TOTAL/STATIC` keyword. If neither `STATIC` nor `TOTAL` have been specified under `ARBITRARY INFLOW`, then the existing switch from the global input parameters is used (default: `TOTAL`).

One profile can be specified for each zone. There can be 100 points in each profile. The normal distance is always assumed to be from $j = 1$ (the reference wall is assumed to be at $j = 1$). *bl1* is the minimum buttline and *bl2* is the maximum buttline.

See Also: `TEST 157`
By default, `USERSPEC` only specifies conditions below a vehicle. That is, the wall ($j = 1$) must be above (higher y) the interior grid points. `TEST 157` specifies that all points within the specified buttline range will be affected, above and below the vehicle. This should be the default, but isn't.

`USERCHEM` *fs bl1 bl2 npts*
  y1 $M\ P\ T\ \alpha\ \beta$
    $sp_1\ \ sp_2\ \ \ldots sp_n$
  y2 $M\ P\ T\ \alpha\ \beta$
    $sp_1\ \ sp_2\ \ \ldots sp_n$
  . . .
  yn $M\ P\ T\ \alpha\ \beta$
    $sp_1\ \ sp_2\ \ \ldots sp_n$

The `USERCHEM` option is identical to the `USERSPEC` option, except that chemistry species mass fractions sp_1, sp_2, …, sp_n are added. Test options can then be set to model the mixing of gas streams which have different chemical compositions. At this time, only mixing can be modeled. The gas streams cannot chemically react.

Note: Only the `STATIC` input mode is available for chemistry.

Part of an example `USERCHEM` input block follows. The file sets up a rectangular jet where the jet composition is a mixture of O_2, CO_2, H_2O, NO_2, and N_2.

```
ARBITRARY INFLOW
   ZONE 1
   USERCHEM 0.0 -10.0 10.0 6
     0.0    0.3  5.70   433.1  0.0  0.0
         0.234  0.0    0.0    0.0  0.766
   123.05  0.3  5.70   433.1  0.0  0.0
```

```
          0.234  0.0    0.0    0.0  0.766
    123.05  1.8  5.66  1940.0  0.0  0.0
          0.096  0.120  0.048  0.0  0.736
    133.75  1.8  5.66  1940.0  0.0  0.0
          0.096  0.120  0.048  0.0  0.736
    133.75  0.3  5.70   433.1  0.0  0.0
          0.234  0.0    0.0    0.0  0.766
    257.0   0.3  5.70   433.1  0.0  0.0
          0.234  0.0    0.0    0.0  0.766
ENDINFLOW
TEST 157 1     USERSPEC ABOVE AND BELOW VEHICLE
```

`USERKE` *fs bl1 bl2 npts*
    y1 M P T α β *val_k* [*val_om*]
    y2 M P T α β *val_k* [*val_om*]
    ...
    yn M P T α β *val_k* [*val_om*]

The `USERKE` option is identical to the `USERSPEC` option, except that the values *val_k* and *val_om* are added to specify inflow turbulence levels when the SST turbulence model is being used. The various options are described above under the `UNIFORM` keyword.

`USERCHEMKE` *fs bl1 bl2 npts*
    y1 M P T α β
        sp_1 sp_2 $\ldots sp_n$ *val_k* [*val_om*]
    y2 M P T α β
        sp_1 sp_2 $\ldots sp_n$ *val_k* [*val_om*]
    ...
    yn M P T α β
        sp_1 sp_2 $\ldots sp_n$ *val_k* [*val_om*]

The `USERCHEMKE` option is identical to the `USERCHEM` option, except that the values *val_k* and *val_om* are added to specify inflow turbulence levels when the SST turbulence model is being used. The various options are described above under the `UNIFORM` keyword.

See Also: `INITIALIZE`, `REINITIALIZE`, `ROTATE`, `TURBULENCE`

Unstructured Grids

Control Functions

`ENDINFLOW`

This optional keyword may be used to end the arbitrary inflow definition.

`STATIC | TOTAL`

Arbitrary inflow conditions specified after this keyword will be considered as static or total, depending which of these is set. By default, the flag is set to the value from the `FREESTREAM` keyword.

`STATIC` may not be used with `USURFACE MASS`.

Note: `TOTAL` is only valid for an ideal gas.

`HOLD_TOTALS`

For points with subsonic inflow, specifying `HOLD_TOTALS` indicates that total temperature, total pressure, and the local flow angles are to be held at their specified values, and the Mach number will be extrapolated. If `HOLD_TOTALS` is not specified, total temperature, Mach number, and the local flow angles will be held at their specified values, and the total pressure will be extrapolated.

For points with supersonic inflow, all conditions are held at their specified values, whether `HOLD_TOTALS` is specified or not.

Note that the `HOLD_CHARACTERISTICS` option is not available for unstructured grids.

`HOLD_TOTALS` is only valid for a perfect gas. The option will be applied at all the arbitrary inflow regions in the zone, and will remain in effect for all following `ZONE` keywords.

`HOLD_TOTALS` only works in conjunction with the `USURFACE` keyword.

`ZONE` *n*

This keyword, which *must* be specified, identifies the zone for which inflow conditions are being set. For example, if zone 2 is an internal jet, conditions other than freestream may be desired at the inflow to zone 2.

Within the `ARBITRARY INFLOW` keyword block, the `ZONE` keyword must come *before* any "Condition Specification" keyword for that zone, but *after* the `HOLD_TOTALS`, keyword for that zone. In addition, inflow conditions may only be specified for one zone at a time.

Condition Specification

`UNIFORM [`$M\ P\ T\ \ \alpha\ \ \beta$`]`
`[`$sp_1\ \ sp_2\ \ \ldots sp_n$`]`

This keyword is used to specify uniform flow at arbitrary inflow boundaries, at the flow conditions listed below. If the flow conditions are omitted, those specified with the `FREESTREAM` keyword are used.

M	Mach number
P	Pressure, psi
T	Temperature, °R
α, β	Angles of attack and yaw, relative to the Cartesian x direction, in degrees
sp_1, sp_2, $\ldots$, sp_n	Species mass fractions. These are required for real gas flows.

Pressure and temperature are static or total, depending on whether `STATIC` or `TOTAL` is specified.

`USURFACE {[FROZEN]` *surface* $M\ P\ T\ \ \alpha\ \ \beta$ `[`$sp_1\ \ sp_2\ \ \ldots sp_n$`] | \`
`MASS` *surface mass area Ttotal* $\alpha\ \ \beta$`}`

This keyword is used with unstructured grids to specify uniform flow at arbitrary inflow boundaries, at the flow conditions listed below. The flow conditions may be specified in terms of Mach number, pressure, and temperature, or in terms of mass flow rate, area, and total temperature. Note that unlike the `UNIFORM` keyword, the flow conditions must be specified.

For the first form of the `USURFACE` keyword, the input is:

surface Surface ID number

M Mach number

P Pressure, psi

T Temperature, °R

α, β Angles of attack and yaw, relative to the Cartesian x direction, in degrees

sp_1, sp_2, …, sp_n Species mass fractions. These are required for real gas flows. Note that unlike the `UNIFORM` and `IJK_RANGE` keywords, here the mass fractions are on the same line as the rest of the flow conditions.

The pressure and temperature listed above may be either static or total, depending on whether `STATIC` or `TOTAL` is specified.

The `FROZEN` option may be specified to freeze the inflow conditions on the surface at the specified values. Note that unlike the `FROZEN` option available with `IJK_RANGE` for structured grids, here the values specified with the keyword are used, not those in the *.cfl* file.

When `USURFACE MASS` is used, the input is:

surface Surface ID number

mass Mass flow rate, $\mathrm{lb_m}$/sec

area Area, in^2

Ttotal Total temperature, °R

α, β These values must be specified, but for `USURFACE MASS` they are ignored, and the flow will automatically be directed normal to the surface.

Note that when `USURFACE MASS` is used, the `FROZEN` option is not available, and *total* temperature must be specified. Either

- `TOTAL` must be specified in the `ARBITRARY INFLOW` keyword block, or
- `TOTAL` must be specified with the `FREESTREAM` keyword, and `STATIC|TOTAL` omitted in the `ARBITRARY INFLOW` block

`USURFACE MASS` may only be used with perfect gases.

Examples

```
ARBITRARY INFLOW
   USURFACE 9 1.1 100. 900. 10. 0.
ENDINFLOW

ARBITRARY INFLOW
   USURFACE MASS 9 939. 1440. 900. 0. 0.
ENDINFLOW
```

AXISYMMETRIC | AXI-SYM — Axisymmetric flow

Structured Grids

`{AXISYMMETRIC | AXI-SYM}` *yc theta*

This keyword allows a two-dimensional structured grid to be run assuming axisymmetric flow. Note that k_{max} must be 1, and that the *.cgd* file is unaware that the grid is axisymmetric or 2D; that is determined at Wind-US run time.

The user-specified values are defined as:

yc Waterline location of rotation axis, in input units (scaled in Wind-US by `XLONG*SCAFAC` and offset by `YNOSE`)

theta Degrees of rotation assumed for metrics. (Changing *theta* should not affect the solution, but will affect convergence. I like 5 degrees.)

BLEED — Bleed region flow rate

Structured Grids

```
BLEED {ibrg blv1 | POROSITY ibrg blv1 blv2 [blv3] | MODEL ibrg mode blv1 blv2 blv3 blv4 | \
      FORCING ibrg blv1 blv2 blv3 | AEDC ibrg}
```

Unstructured Grids

```
BLEED {ibrg blv1 | POROSITY ibrg blv1 blv2 blv3 | FORCING ibrg blv1 blv2 blv3}
```

The effect of bleed on the flow can be modeled, if bleed regions were identified in the grid file. The parameters discussed below identify the bleed rate for each region, for a specific solution. If a bleed region is not named in this file, its bleed rate is set to zero.

There are five possible bleed modes for structured grids, and three for unstructured grids, as described below. Unless noted otherwise, the keywords apply to both structured and unstructured grids.

However, with unstructured grids bleed is only allowed for perfect gases and non-rotating grids. Also, with unstructured grids, the bleed boundary condition is applied at the cell faces, but the flow field values written to the *.cfl* file for post-processing are at the nodes. The results may thus be slightly different around the edges of the bleed region with structured and unstructured grids.

```
BLEED ibrg blv1
```

ibrg Bleed region number from *.cgd* file

blv1 Normalized bleed flow rate

blv1 can also be thought of as the mass flow ratio for the bleed region. The actual bleed mass flow is calculated as

$$\dot{m}_b = \mathit{blv1}(\rho_\infty U_\infty A_c)$$

where A_c is an arbitrarily set reference "capture area" that you must specify, in either GMAN (using the `CAPTURE AREA` command, or the `BOUNDARY COND.` menu) or MADCAP (using "Set Capture Area" from the "Boundary Conditions" menu), in each zone of the grid file that contains bleed areas.

The bleed velocity will automatically be limited to Mach 1.

Although this is intended as a bleed model, it can also be used for blowing by setting *blv1* to a negative value.

```
BLEED POROSITY ibrg blv1 blv2 blv3
```

[There are some questions about the coding for the porous bleed model that need to be resolved. This model should be therefore used with caution.]

ibrg Bleed region number from *.cgd* file *blv1* Back pressure p_{plen}, in psia

blv2 Porosity

blv3 Discharge coefficient; may be defaulted for structured grids

With this model, the velocity at the wall will be computed from the local pressure p in the flow field, and the specified back pressure p_{plen}. If $p > p_{plen}$, the flow will be out of the computational domain (i.e., bleed). If $p < p_{plen}$, the flow will be into the computational domain (i.e., blowing).

For unstructured grids, the discharge coefficient must be specified. For structured grids, however, it may be omitted. In this case, for bleed a default value is computed from the specified back pressure and the local flow conditions, using the empirically-based method of Dittrich and Graves (1956). For blowing, the default value for the discharge coefficient is 0.6.

`BLEED MODEL` *ibrg mode blv1 blv2 blv3 blv4*

This bleed mode is only available for structured grids.

This keyword specifies use of the empirical bleed model of Mayer and Paynter (1994).

The input parameter *ibrg* is the bleed region number from the *.cgd* file. The input data for the bleed model is given by the values of *blv1* through *blv4*. Various combinations of values may be specified, depending on the *mode*, as described below.

mode	*blv1*	*blv2*	*blv3*	*blv4*
1	p_{plen}	Porosity	*qsmode*	N_{bl}
2	p_{plen}	Porosity	*qsmode*	
3	p_{plen}	Porosity		M
4	Q_{sonic}	Porosity	*qsmode*	M

In the above table, p_{plen} is the bleed plenum static pressure, N_{bl} is the number of grid points in the boundary layer, Q_{sonic} is the sonic mass flow coefficient (described below), and M is the local Mach number at the edge of the boundary layer. The parameter *qsmode* is an integer from 1 to 3 defining how Q_{sonic} is to be computed, as follows:

1	Set $Q_{sonic} = 1$
2	Compute Q_{sonic} for 90° holes
3	Compute Q_{sonic} for 20° holes

In the Mayer-Paynter model, the bleed velocity is given by the formula

$$V_{bleed} = Q_{sonic}\,\Phi\,\Gamma\,T\,\frac{p_T}{p}\,\frac{1}{\sqrt{T_T}}$$

where Φ is the porosity, p and T are the local static pressure and temperature, and p_T and T_T are the local total pressure and temperature. "Local" means at the edge of the boundary layer at the location of the grid point within the bleed region. The parameter Γ is a function of the specific heat ratio γ.

$$\Gamma = \left(1 + \frac{\gamma - 1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

Central to the model is Q_{sonic}, the sonic mass flow coefficient, defined as

$$Q_{sonic} = \frac{\dot{m}_{bleed}}{\dot{m}_{max}} = f\left(\alpha, M, \frac{p_{plen}}{p_T}\right)$$

where $\dot{m}_{bleed}$ is the actual bleed flow rate and $\dot{m}_{max}$ is the maximum theoretical bleed flow rate.

Q_{sonic} is a function of the bleed hole angle α, the local Mach number M, and the ratio of the plenum pressure p_{plen} to the local pressure p. The functional relationship is in the form of tabulated experimental data for circular bleed holes at angles of 20° (McLafferty and Ranard, 1958) and 90° (Syberg and Hickox, 1972).

`BLEED FORCING` *ibrg blv1 blv2 blv3*

This mode allows an oscillating normal velocity bleed boundary condition to be specified.

ibrg Bleed region number from *.cgd* file

blv1 Amplitude of the normal velocity oscillation (ft/sec)

blv2 Frequency of the oscillation (Hz)

blv3 Phase offset of the oscillation (deg)

`BLEED AEDC` *ibrg*

ibrg Bleed region number from *.cgd* file

This bleed mode is only available for structured grids.

When the `AEDC` keyword is specified, the bleed region uses the AEDC wind tunnel wall correction correlations. (Note: the entire boundary must be flagged as bleed, not only the porous region.) This condition is hard-wired for the $j = 1$ boundary and the AEDC wind tunnel and is *not intended for general use.*

See Also: `BLOW`, `MASS FLOW`, `TEST 46`, `TEST 67`

BLOW — Inject vectored flow over a selected region

Structured Grids

```
BLOW {ibreg mdot T_inj [STATIC|TOTAL] \
         angle_inc [ABOUT_Z [angle_azi] | ABOUT_NORMAL [angle_azi]] | \
      PLENUM ibreg P_t T angle | \
      SURFACE ibreg P_t T_t \
         angle_inc [ABOUT_Z [angle_azi] | ABOUT_NORMAL [angle_azi]] | \
      VALVE ibreg P_t T_t angle}
[BLOW FORCING ibreg {MASS|VELOCITY} amp freq phase]
[BLOW MASS [FRACTIONS] ibreg sp_1 sp_2 ...sp_n]
```

Unstructured Grids

```
BLOW {ibreg mdot T_inj [STATIC|TOTAL] \
         angle_inc [ABOUT_Z [angle_azi] | ABOUT_NORMAL [angle_azi]] | \
      PLENUM ibreg P_t T angle | \
      SURFACE ibreg P_t T_t \
         angle_inc [ABOUT_Z [angle_azi] | ABOUT_NORMAL [angle_azi]]}
[BLOW FORCING ibreg {MASS|VELOCITY} amp freq phase]
```

Porous wall cooling over a selected region can be simulated using this keyword. The region must be identified as a bleed region in the grid file. This option is intended for mass inflow only (i.e., $P_t >$ local P_s). It won't work well for grids that are skewed at the wall, resulting in blowing mass flow errors.

Blowing may also be modeled using the first two forms of the BLEED keyword (i.e., BLEED and BLEED POROSITY).

The definition of the blowing direction is general enough that a blowing region on the upper and/or lower surface of a wing will be treated consistently with a single specification. However, one should avoid specifying a blowing region in more severe cases, such as the normal part of a backward-facing step, where the surface normal is purely in the x direction.

There are four possible blowing modes for structured grids, and three for unstructured grids, as described below. Unless noted otherwise, the keywords apply to both structured and unstructured grids.

However, with unstructured grids blowing is only allowed for perfect gases and non-rotating grids. Also, with unstructured grids, the blowing boundary condition is applied at the cell faces, but the flow field values written to the *.cfl* file for post-processing are at the nodes. The results may thus be slightly different around the edges of the blowing region with structured and unstructured grids.

```
BLOW ibreg mdot T_inj [STATIC|TOTAL] \
        angle_inc [ABOUT_Z [angle_azi] | ABOUT_NORMAL [angle_azi]]
[BLOW FORCING ibreg MASS|VELOCITY amp freq phase]
```

ibreg	Bleed region number from *.cgd* file
mdot	Injected mass flow in region *ibreg* ($\mathrm{lb_m/sec}$)

T_{inj} Temperature of injected flow (°R). Either static or total temperature may be specified, as indicated by the optional choice of `STATIC` or `TOTAL`. (However, `TOTAL` may not be used when `VELOCITY` is used with `BLOW FORCING`.) The default is `STATIC`.

angle_inc Blowing inclination angle (degrees); must be > 0

angle_azi Blowing azimuthal angle (degrees). The default is 0.0.

The blowing direction is set by the input inclination and azimuthal angles.

The inclination angle is the angle between the blowing direction and the projection of the x axis onto the surface.

If `ABOUT_Z` is specified, the azimuthal angle is the angle between the blowing direction and the projection of the surface normal onto a constant z plane. Starting from the projection of the x axis onto the surface, the blowing direction is thus determined by rotating about the projection of the surface normal onto a constant z plane by the azimuthal angle, then "up" from the surface by the inclination angle.

If `ABOUT_NORMAL` is specified, the azimuthal angle is the angle between the blowing direction and the surface normal itself. Again starting from the projection of the x axis onto the surface, the blowing direction is thus determined by rotating about the surface normal by the azimuthal angle, then "up" from the surface by the inclination angle.

If neither `ABOUT_Z` nor `ABOUT_NORMAL` is specified, `ABOUT_Z` is assumed, and *angle_azi* will have its default value of 0.0.

`BLOW FORCING` may be used with this blowing mode to add an oscillatory component to the blowing velocity. The added blowing is specified as either a mass flow or velocity, depending on the choice of `MASS` or `VELOCITY`. (If `VELOCITY` is used, the static temperature must be specified with the `BLOW` keyword.) The direction of the added blowing will be the same as the mean blowing, as determined by *angle_inc* and *angle_azi*.

ibreg Bleed region number from *.cgd* file

amp Amplitude of the oscillation for the added blowing (lb_m/sec for `MASS`, ft/sec for `VELOCITY`)

freq Frequency of the oscillation (deg/sec)

phase Phase offset of the oscillation (deg)

This blowing mode may not be used for multi-species flows.

`BLOW PLENUM` *ibreg* P_t T *angle*
`[BLOW FORCING` *ibreg* `MASS|VELOCITY` *amp freq phase*`]`

ibreg Bleed region number from *.cgd* file

P_t Plenum total pressure (psi)

T Plenum static temperature (°R)

angle Blowing angle relative to x-y plane (degrees)

If the flowfield static pressure P_s becomes greater than the plenum total pressure P_t, the plenum total pressure will be automatically increased to $1.005P_s$ to maintain a blowing boundary condition. Setting `TEST 52` will notify the user when this occurs.

`BLOW FORCING` may be used with this blowing mode to add an oscillatory component to the blowing velocity. The added blowing is specified as either a mass flow or velocity, depending on the choice of `MASS` or `VELOCITY`. The direction of the added blowing will be the same as the mean blowing, as determined by *angle*. The input parameters are the same as for the first blowing mode, described above.

This blowing mode may not be used for multi-species flows.

`BLOW SURFACE` *ibreg* P_t T_t `\`
        angle_inc `[ABOUT_Z [`*angle_azi*`] | ABOUT_NORMAL [`*angle_azi*`]]`
`[BLOW FORCING` *ibreg* `MASS|VELOCITY` *amp freq phase*`]`

ibreg Bleed region number from *.cgd* file

P_t Plenum total pressure (psi)

T_t Plenum total temperature (°R)

angle_inc Blowing inclination angle (degrees); must be > 0

angle_azi Blowing azimuthal angle (degrees). The default is 0.0.

With this boundary condition, blowing will occur whenever the local flowfield static pressure is less than the specified plenum total pressure. If the flowfield static pressure is greater than the plenum total pressure, the velocity normal to the wall at that point is set to zero (i.e., a solid wall with no blowing or bleed). Unlike the `BLOW VALVE` capability, with `BLOW SURFACE` blowing is turned on or off locally, on a point-by-point basis.

The blowing velocity is also constrained to subsonic values.

The blowing direction is set by the input inclination and azimuthal angles. The angles are defined in the same way as when the standard `BLOW` keyword is used to specify a constant blowing mass flow, as described above.

The `BLOW SURFACE` keyword may not be used for multi-species flows, except for Liu-Vinokur equilibrium air chemistry.

If the `TEST 195` option is set, a message will be written in the list output (*.lis*) file whenever the blowing is turned off because the flowfield static pressure is too large. Note, however, that this is a five-line message written for each iteration and each "closed" node, and could cause the *.lis* file to become very large very quickly.

`BLOW FORCING` may be used with this blowing mode to add an oscillatory component to the blowing velocity. The added blowing is specified as either a mass flow or velocity, depending on the choice of `MASS` or `VELOCITY`. The direction of the added blowing will be the same as the mean blowing, as determined by *angle_inc* and *angle_azi*. The input parameters are the same as for the first blowing mode, described above.

`BLOW VALVE` *ibreg* P_t T_t *angle*
`[BLOW MASS [FRACTIONS]` *ibreg* sp_1 sp_2 $\ldots sp_n$`]`

ibreg Bleed region number from *.cgd* file

P_t Plenum total pressure (psi)

T_t Plenum total temperature (°R)

angle Blowing angle relative to x-y plane (degrees)

$sp_1\ sp_2 \ldots sp_n$ Mass fractions of injected species. The default values are those specified in the `CHEMISTRY` keyword block.

This blowing mode is only available for structured grids.

If the flowfield static pressure P_s becomes greater than the plenum total pressure P_t at any point within the blowing region, blowing will be shut off for the entire region, and the surface will be treated as a solid wall. A `*VLV*` line is written to the list output (*.lis*) file whenever the valve changes status.

For multi-species flow, when `BLOW MASS FRACTIONS` is specified the mass fractions should be specified in the same order as the species in the chemistry data (*.chm*) file, described in Section 7.9. However, if the species have been re-ordered using the `SPECIES` keyword in the `CHEMISTRY` keyword block, and the `BLOW MASS FRACTIONS` keyword comes after the `CHEMISTRY` keyword block in the input data (*.dat*) file, then the mass fractions should be specified in the new species order.

`BLOW MASS FRACTIONS` only works with `BLOW VALVE`. Note that it is a separate line, not a continuation of the `BLOW VALVE` keyword.

With `BLOW VALVE`, the blowing region may extend to more than a boundary surface, and may also be split between zones. Note, however, that when a blowing region is split between multiple processors, the separate sub-regions act independently until the end of a cycle. If the flowfield static pressure grows large enough in one sub-region to close the valve but not in the other sub-region(s), the valve will close for the first sub-region, but not on the others until the end of the cycle. The reverse situation (i.e., opening a closed valve) may also occur. This may be prevented by running one iteration per cycle; as a practical matter, it is not expected to cause problems with the default of five iterations per cycle.

See Also: `BLEED`, `TEST 46`, `TEST 52`, `TEST 67`, `TEST 178`, `TEST 195`

BL_INIT — Boundary layer initialization

Structured Grids

```
BL_INIT nb ixs str igrs [delt] nbli nzone
```

For ideal gases (i.e., no CHEMISTRY) and structured grids, the BL_INIT keyword may be used to initialize a j or k boundary with a laminar or turbulent flat plate boundary layer. The user-specified values are defined as:

nb A number from 1 to 4 indicating which boundary to initialize

1	for $j = 1$
2	for $j = j_{max}$
3	for $k = 1$
4	for $k = k_{max}$

ixs Integer indicating method for specifying the axial location to start the boundary layer:

1	to specify the i index
2	to specify the x station

str i index or x location to start the boundary layer, depending on the value of *ixs*

igrs Integer indicating method for specifying the initial height of the boundary layer:

1	to specify the number of grid points from the wall
2	to specify the thickness
3	to compute thickness from initial x station

delt Number of grid points in boundary layer (if $igrs = 1$), or boundary layer thickness (inches) (if $igrs = 2$)

nbli Integer indicating type of boundary layer and whether to keep constant thickness or grow with x

1	Turbulent profile, growing with x
-1	Turbulent profile, constant thickness
2	Laminar profile, growing with x
-2	Laminar profile, constant thickness

nzone Zone number for initialization

0	All zones
> 0	Zone *nzone* only

A flat plate temperature distribution will also be constructed consistent with the wall temperature boundary condition of either adiabatic or constant temperature wall, as specified using the WALL TEMPERATURE keyword.

Note: BL_INIT cannot currently do more than one boundary in each zone without over-writing itself.

BOUNDARY-DAMP | BDAMP — Boundary damping (block)

Structured Grids

```
{BOUNDARY-DAMP | BDAMP}
   ZONE range1[,range2[, ...  rangen]]
   BOUNDARY bnd1:bnd2
   [POINTS n]
   [SECOND c2]
   [FOURTH c4]
   [NOSMOOTHING [NI m1] [NJ m2] [NK m3]]
{END-BOUNDARY-DAMP | ENDBDAMP}
```

This keyword may be used with structured grids to apply second- and fourth-order smoothing to damp waves in the vicinity of computational boundaries. It is also possible to turn off smoothing near any boundary for any numerical operator (ξ, η, or ζ). This option must be used with the `SMOOTHING` keyword and `TEST 49 2`. The user-specified values are defined as:

range Zone specification range, in one of the following forms:

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
begzone:	Selects all zones from *begzone* to `MAXZONE`, the total number of zones in the grid file
:*endzone*	Selects all zones from 1 to *endzone*
`ALL`	Selects all zones

bnd1 Starting boundary (0 to begin at boundary 1). The values 1–6 correspond to the $i = 1$, $i = i_{max}$, $j = 1$, $j = j_{max}$, $k = 1$, and $k = k_{max}$ boundaries, respectively.

bnd2 Ending boundary (0 to end at last boundary)

n Number of points into the domain over which boundary damping is to be applied

c2 Second-order smoothing coefficient

c4 Fourth-order smoothing coefficient

The `NOSMOOTHING` keyword is used to turn off smoothing (as specified using the `SMOOTHING` keyword) for the most recently specified `ZONE` and `BOUNDARY`. The keywords `NI`, `NJ`, and/or `NK` specify that smoothing is to be turned off for the ξ, η, and/or ζ operator, respectively, for boundaries *bnd1* through *bnd2*. When `NOSMOOTHING` is used, at least one of `NI`, `NJ`, and `NK` must be specified.

m_1, m_2, m_3 Number of points into the domain on boundaries *bnd1* through *bnd2* over which smoothing is to be turned off

Example

```
BOUNDARY-DAMP
   ZONE 2:4 BOUNDARY 1:3 POINTS 15 SECOND .01 FOURTH .03
   ZONE 3:3 BOUNDARY 4:4 POINTS 10 SECOND .02 FOURTH .01
   ZONE 5:5
   BOUNDARY 2:2
   NOSMOOTHING NI 31 NJ 21
END-BOUNDARY-DAMP
```

See Also: SMOOTHING, TEST 49

BOUNDARY TVD — Boundary total variation diminishing operator flag

Structured Grids

```
BOUNDARY TVD [{OFF | FACTOR factor} [ZONE range1[,range2[, ...  rangen]] \
   [BOUNDARY {ALL | I1 | IMAX | J1 | JMAX | K1 | KMAX | OVERLAP}]]]
```

This keyword controls the TVD flux limiter in the explicit operator at the specified coupled boundaries in structured grids. The same type of limiter (minmod, Koren, or van Albada) will be used as for the internal scheme.

FACTOR specifies the "compression" parameter for the TVD operator at the specified boundaries, which controls the amount of limiting. Larger numbers result in less limiting towards a first order operator. Setting *factor* to zero is equivalent to a first order operator, one corresponds to no overshoots, and two allows some increase in interface value over surrounding values.

The boundary TVD limiter must be more limiting than the interior TVD limiter for it to have any additional effect. I.e., the value *factor* must be less than the value used for the internal scheme.

In the zone specification, the *range* parameter(s) must be one of the following forms:

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
begzone:	Selects all zones from *begzone* to MAXZONE, the total number of zones in the grid file
:*endzone*	Selects all zones from 1 to *endzone*
ALL	Selects all zones

By default, boundary TVD is on at all boundaries. If the BOUNDARY TVD keyword is not specified at all, the compression parameter will be the same as is used for the internal scheme. If BOUNDARY TVD is specified, but without additional keywords, the default value for *factor* will be used, as listed for the TVD keyword.

Note that if a particular zone (or zones) is to be specified, then either "OFF" or "FACTOR *factor*" must also be specified. And, if a particular boundary is to be specified, then the zone(s) must also be explicitly specified.

See Also: TVD

CFL# — CFL/time step specification

Structured Grids

```
{CFL# | TIMESTEP} { \
   [MODE 1] [CFL | SECONDS] cfl [zone_selector [ityp]] | \
   [MODE 2] [CFL | SECONDS] INCREMENT cfl1 cflmax cflfac inccfl istart \
      [zone_selector [ityp]] | \
   MODE 3 [DT dt] [CFLMIN cflmin] [CFLMAX cflmax] [ITIME itime] [zone_selector]}
```

Unstructured Grids

```
{CFL# | TIMESTEP} { \
   [MODE 1] [CFL] cfl [zone_selector] | \
   [MODE 2] [CFL] INCREMENT cfl1 cflmax cflfac inccfl istart \
      [zone_selector]}
```

This keyword allows the user to specify the CFL number or time step for all zones, or on a zone-by-zone basis. All keywords and parameters must be on one line in the data file. If this keyword is not used, a constant CFL number of 1.3 is used, equivalent to specifying ”`CFL# CFL 1.3`”.

Structured Grids

There are three different options for structured grids, as specified by the `MODE` value. Note that the `MODE` keyword is optional for modes 1 and 2, but required for mode 3. (Modes 1 and 2 are distinguished in the code by whether or not the word `INCREMENT` is present.)

```
{CFL# | TIMESTEP} [MODE 1] [CFL | SECONDS] cfl [zone_selector [ityp]]
```

In this mode, the CFL number or time step is specified directly, by the input value *cfl*.

`CFL` A CFL number is being specified. This is the default, and should be used for steady flow problems.

`SECONDS` The time step is being specified in seconds. This option is generally used for unsteady flow problems.

When a CFL number is being specified, the value of *ityp* may be set to 1 to indicate that a global time step (i.e., constant in space) should be used, equal to the minimum value in the zone. This allows the time step to be determined through a CFL number for unsteady flow problems. Currently, this option is only available for single-zone grids. When a CFL number is specified, and *ityp* $= 0$ or is omitted, a local time step (i.e., varying in space) will be used.

```
{CFL# | TIMESTEP} [MODE 2] [CFL | SECONDS] INCREMENT cfl1 cflmax cflfac inccfl istart \
   [zone_selector [ityp]]
```

In this mode, the CFL number or time step will be gradually increased as the calculation proceeds. The `CFL` and `SECONDS` options have the same meaning as for mode 1, again with `CFL` as the default. The increase in the CFL number or time step is controlled by the following input values:

cfl1 CFL number or time step for iteration *istart*

cflmax Maximum CFL number or time step allowed

cflfac Factor which multiplies the CFL number or time step every *inccfl* iterations

inccfl Iteration increment at which the CFL number or time step is multiplied by *cflfac*. The multiplication is done whenever mod (iteration, *inccfl*) = 1.

istart Starting iteration in the increment calculation. Note that the iteration values are cumulative, starting from the initial run. I.e., to gradually increase the CFL number at the beginning of a restart case, *istart* should be set to the value of the iteration in the existing *.cfl* file, from the previous run.

As in mode 1, when a CFL number is being specified for a single-zone grid, the value of *ityp* may be set to 1 to indicate that a global time step (i.e., constant in space) should be used, equal to the minimum value in the zone.

```
{CFL# | TIMESTEP} MODE 3 [DT dt] [CFLMIN cflmin] [CFLMAX cflmax] [ITIME itime] \
   [zone_selector]
```

This mode uses the time step calculation procedure originally used in the OVERFLOW code.

itime A flag indicating the type of time step to be used

0 Time-accurate run (i.e., time step is constant in space)

1 Time step scaled by local metric Jacobian, with fudge factor of 0.005 to keep the time step from getting too small for really tiny cells

2 Time step scaled by local metric Jacobian, without a fudge factor

3 Constant CFL number equal to *cflmax*

dt Time step parameter. For *itime* = 0 (i.e., time-accurate cases), this is the time step in seconds nondimensionalized by L_r/a_r, where L_r is the grid reference length and a_r is the freestream speed of sound. For *itime* = 1 and 2, this is a CFL number, before scaling by the local metric Jacobian. For *itime* = 3, *dt* is not used. The default value is 0.5.

cflmin, cflmax For *itime* = 3, the CFL number is set to *cflmax*, and *cflmin* is not used. The CFL number is defined using the sum of the maximum eigenvalues in each coordinate direction.

For other *itime* values, *cflmin* and *cflmax* are used to limit the CFL number to values within the specified range. A value of 0.0 indicates no limiting. If either *cflmin* or *cflmax* is negative, the absolute values are used, and the CFL number is defined using the method of Gnoffo, with a viscous correction by Tannehill. If both *cflmin* and *cflmax* are non-negative, the usual one-dimensional (inviscid) CFL number definition using the maximum eigenvalue is used.

The default values are both 0.0.

Examples

Set the CFL number to 1.5 in all zones.

```
CFL# CFL 1.5
```

Set the CFL number to 1.5 in zones 1 and 5, and 0.7 in zones 2, 3, and 4.

```
CFL# CFL 1.5 ZONE 1,5
CFL# CFL 0.7 ZONE 2:4
```

The following example sets the CFL number to 1.0, computes the corresponding time step at every point in the grid, finds the minimum of those time steps, and resets the time step at every point to that minimum value. This allows the time step to be set for an unsteady flow problem by specifying a CFL number. Note that even though this may only be done for single-zone grids, the syntax requires that the zone be explicitly specified.

```
CFL# CFL 1.0 ZONE 1 1
```

Set the time step equal to 1×10^{-6} seconds at every point.

```
CFL# SECONDS 0.000001
```

The next example sets the CFL number to 0.5 for the first 500 iterations, then increases it by a factor of 1.1 every 100 iterations. The maximum value allowed will be 2.0, so the actual final CFL number will be some value just below 2.0. (For this example, it's 1.899.)

```
CFL# CFL INCREMENT 0.5 2.0 1.1 100 501
```

This example uses the mode 3 time step calculation procedure to set the time step parameter to 0.1, and defaults the remaining input parameters, causing the actual time step to be scaled by the local metric Jacobian with the 0.005 fudge factor, with no minimum or maximum value.

```
CFL# MODE 3 DT 0.1
```

In this example the mode 3 time step calculation procedure is used to set the time step parameter to 0.5. The actual time step will be scaled by the local metric Jacobian with the 0.005 fudge factor, with minimum and maximum CFL numbers of 1.0 and 5.0. Since the minimum and maximum values are specified as positive numbers, the standard one-dimensional (inviscid) CFL number definition using the maximum eigenvalue is used.

```
CFL# MODE 3 DT 0.5 CFLMIN 1.0 CFLMAX 5.0
```

The next example uses the mode 3 time step calculation procedure to set the time step parameter to 0.05. The actual time step will be scaled by the local metric Jacobian without the 0.005 fudge factor, with minimum and maximum CFL numbers of 1.0 and 5.0. Since the minimum and maximum values are specified as negative numbers, the CFL definition of Gnoffo is used, with a viscous correction by Tannehill.

```
CFL# MODE 3 DT 0.05 ITIME 2 CFLMIN -1.0 CFLMAX -5.0
```

Use the mode 3 time step calculation procedure to set the CFL number to a constant value of 1.3.

```
CFL# MODE 3 ITIME 3 CFLMAX 1.3
```

Use the mode 3 time step calculation procedure for an unsteady case, with the nondimensional time step set to a constant value of 0.05.

```
CFL# MODE 3 ITIME 0 DT 0.05
```

The following example uses the mode 3 time step calculation procedure for an unsteady case, again with a specified nondimensional time step of 0.05. In this case, however, if the specified time step results in a CFL number at some point in the flow field less than 0.25 or greater than 5.0, the actual time step throughout the flow field will be reset to the corresponding value.

```
CFL# MODE 3 ITIME 0 DT 0.05 CFLMIN 0.25 CFLMAX 5.0
```

See Also: CROSSFLOW

Unstructured Grids

There are two options for unstructured grids, again specified by the MODE value. Note that the MODE keyword is optional. (Modes 1 and 2 are distinguished in the code by whether or not the word INCREMENT is present.)

For unstructured grids, a larger CFL value can usually be used than the default of 1.3, which is suitable for structured grids. Suggested values for unstructured grids are 10 at the start of a calculation, and as high as 50 for later runs.

```
{CFL# | TIMESTEP} [MODE 1] [CFL] cfl [zone_selector]
```

In this mode, the CFL number or time step is specified directly, by the input value *cfl*. The separate TIMEMARCHING keyword determines whether *cfl* is interpreted as a CFL number, resulting in a local time step (i.e., varying in space), or as a global time step (i.e., constant in space). For steady flow calculations, set *cfl* to the desired CFL number, and also use

```
TIMEMARCHING VARIABLE-DT
```

For unsteady calculations, set *cfl* to the desired time step in seconds, and use

```
TIMEMARCHING CONSTANT-DT
```

```
{CFL# | TIMESTEP} [MODE 2] [CFL] INCREMENT cfl1 cflmax cflfac inccfl istart \
   [zone_selector]
```

In this mode, the CFL number will be gradually increased as the calculation proceeds. The increase in the CFL number is controlled by the following input values:

cfl1 CFL number for iteration *istart*

cflmax Maximum CFL number allowed

cflfac Factor which multiplies the CFL number every *inccfl* iterations *inccfl* Iteration increment at which the CFL number is multiplied by *cflfac*. The multiplication is done whenever $\mod(\text{iteration}, \textit{inccfl}) = 1$.

istart Starting iteration in the increment calculation. Note that the iteration values are cumulative, starting from the initial run. I.e., to gradually increase the CFL number at the beginning of a restart case, *istart* should be set to the value of the iteration in the existing *.cfl* file, from the previous run.

This mode should only be used for steady flow calculations, with a local time step. If this mode is inadvertantly used in conjunction with

```
TIMEMARCHING CONSTANT-DT
```

the value of *cfl1* will be interpreted as the time step in seconds, and the remaining input parameters will be ignored.

See Also: `TIMEMARCHING`

CGNSBASE — Use CGNS files

```
CGNSBASE basename
```

This keyword specifies that the grid and flow data are obtained from, and written to, CGNS (CFD General Notation System) files, not common files. The user-specified *basename* is the name of the `CGNSBase_t` node in the grid and flow files.[26]

It should be noted that, strictly speaking, there is no notion of a CGNS *file*, only of a CGNS *database* implemented within one or more ADF (Advanced Data Format) files. We nevertheless use the terminology "CGNS file" in the Wind-US documentation. In addition, a true CGNS database has a single `CGNSBase_t` node as its root. In the current Wind-US implementation, however, the grid and flow solution are stored in separate files, with both files having their own `CGNSBase_t` node with the same *basename*.

When CGNS files are used, the extensions for the grid and flow files must be *.cgd* and *.cfl*, respectively, the same as when common files are used. If the `CGNSBASE` keyword is used, the files are read as CGNS files. If the `CGNSBASE` keyword is not used, they are assumed to be common files.

Wind-US supports the most common CGNS features, but not all. Some specific limitations on the implementation of CGNS in Wind-US are listed below.

- Many Wind-US input options may be specified on a zonal basis, using the zone number to identify the zone. In the CGNS standard, zones are identified by a name. When CGNS files are used in Wind-US, it is assumed that the zone number maps to the zone's position in an alphanumerically sorted list of zone names.

  Note that the naming convention `Zone`*n*, where *n* is the zone number, is alphanumeric only up to `Zone9`. `Zone10` through `Zone19` would get sorted between `Zone1` and `Zone2`, and so on. However, spaces are allowed in names, so "`Zone  `*n*", with two spaces, (e.g., `Zone  1`, `Zone  2`, . . . , `Zone 99`, `Zone100`, . . .) is alphanumeric up to `Zone999`.

- The CGNS default names "`GridCoordinates`" and "`FlowSolution`" are used for the CGNS `GridCoordinates_t` and `FlowSolution_t` nodes. For each zone, only one grid and one flow solution are stored.

- In a CGNS database, the scaling data must be stored with the data itself, but the units to be used may be stored with the data or higher in the node tree. The Wind-US implementation assumes that the units are stored with the data.

- If grid velocities are stored in the grid file, it is assumed that the units are ft/sec.

- The CGNS nodes for storing time-dependent data are not yet supported in Wind-US.

- For overlapping grids, CGNS allows hole points to be identified using multiple `OversetHoles_t` nodes. Wind-US currently assumes that all hole points in a zone are identified in a single `OversetHoles_t` node, using a `PointList`.

- Wind-US writes convergence and time history information to the list output (*.lis*) and time history (*.cth*) files, respectively, not to a CGNS file.

[26] Detailed information on the CGNS standard may be found at the CGNS web site, at http://cgns.sourceforge.net/.

There are also some Wind-US features and capabilities that are not supported by the current CGNS standard. These include chemistry and MFD flows, specified boundary layer transition, and bleed boundary conditions. Several proposals are pending to extend the CGNS standard, but for now CGNS files created by Wind-US for these types of flows may not be fully CGNS compliant, and should be considered unique to the Wind-US implementation.

CHEMISTRY — Chemistry model selection (block)

```
CHEMISTRY
   FILE {filename [LOCAL]}
   [SPECIES S1 S2 ...Sm]
   {FROZEN | FINITE [RATE]}
   [FUEL [AIR] [RATIO] value]
   [LIU-VINOKUR 2]
   [THERMO9]
   MASS [FRACTIONS] {AIR | sp1 sp2 ...spn}
   OMIT [THIRD-BODY] S1 S2 ...Sm ZONE range1[,range2[, ...  rangen]]
   [VISCOSITY {SUTHERLAND | WILKE | KEYE | CONSTANT vis | TUNNEL9 | \
               CUSTOM c1 c2}]
ENDCHEMISTRY
```

This option allows the user to specify the real gas chemistry mode and input data for the desired species and reactions.

Note: The `ARBITRARY INFLOW` keyword block, if used, must come after the `CHEMISTRY` keyword block in the input data (*.dat*) file.

The various elements of the `CHEMISTRY` input block are defined as follows:

`CHEMISTRY`

Defines the beginning of the `CHEMISTRY` block

`FILE {`*filename* `[LOCAL]}`

Specifies the chemistry data file containing the thermodynamic data, finite rate coefficients, and transport property data for Wilkes' law. (See Section 7.9 for the file format.) If the chemistry data file is located in the directory that Wind-US files (*.cfl*, *.cgd*, etc.) are running the keyword `LOCAL` must be specified.

`SPECIES` S_1 S_2 $\ldots S_m$

Order the species as given by the species names S_1 through S_m. If this keyword is not used, the species are ordered as listed in the chemistry data file, described in Section 7.9.

The re-ordering is done *after* all keywords in the `CHEMISTRY` block have been processed.

`{FROZEN | FINITE [RATE]}`

`FROZEN`	Selects frozen chemistry
`FINITE [RATE]`	Selects finite rate chemistry

Note that the finite rate chemistry capability isn't yet fully implemented for unstructured grids.

THERMO9

Simulate AEDC's Tunnel 9 facility with pure nitrogen, using a real gas table look-up of thermodynamic properties. This option is only available for structured grids.

FUEL [AIR] [RATIO] *value*

value specifies the fuel-air ratio for H_2-air combustion (two-reaction global model).

LIU-VINOKUR 2

Selects the Liu and Vinokur equilibrium air curve fits. Valid to 50000 K, does not output species.

MASS [FRACTIONS] {AIR | sp_1 sp_2 $\ldots sp_n$}

Specifies the freestream (reference) mass fractions of the species. The mass fractions are specified in the same order as the species in the chemistry data (*.chm*) file, described in Section 7.9.

The keyword AIR indicates use of air mass fractions.

OMIT [THIRD-BODY] S_1 S_2 $\ldots S_m$ ZONE *range1* [,*range2* [, ... *rangen*]]

This keyword allows control of the reacting species in a finite-rate chemistry solution on a zonal basis. Reactions leading to the production or destruction of the species given by S_1 through S_m will be eliminated in the selected zones. In addition, if the THIRD-BODY keyword parameter is used, *any* reaction involving the named species will be eliminated. The species will still be convected and diffused, maintaining conservation at zone boundaries.

Eliminating reactions in zones where they aren't relevant improves the overall efficiency of the calculation in two ways. First, the time required to perform the unnecessary computations is eliminated. And second, the stiffness of the system of equations is reduced, leading to faster convergence and greater stability.

In the zone specification, the range parameter(s) may be

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
ALL	Selects all zones

Multiple OMIT keywords are allowed, with conflicting input resolved by using the latter of the conflicting entries.

VISCOSITY {SUTHERLAND | WILKE | KEYE | CONSTANT *vis* | TUNNEL9 | CUSTOM c_1 c_2}

Selects the transport property equations. For unstructured grids, only the SUTHERLAND and WILKE options are available. See the VISCOSITY keyword for details.

ENDCHEMISTRY

Defines the end of the CHEMISTRY block.

See Also: TEST 71

General and Standard Chemistry Packages

The chemistry data files supplied with Wind-US are summarized in Table 1.[27]

Table 1: General and Standard Chemistry Packages

Species	File(s)	T_{max}	*Nc*	*Nr*	*3d*
O_2, NO, O, N, N_2	*air-5sp-std-06k.chm* *air-5sp-gen-06k.chm*	6000 K	1	5	V
O_2, NO, O, N, N_2	*air-5sp-std-15k.chm* *air-5sp-gen-15k.chm*	15000 K	3	5	V
O_2, NO, O, N, N_2	*air-5sp-std-30k.chm* *air-5sp-gen-30k.chm*	30000 K	5	5	V
O_2, NO, O, N, NO^+, e^-, N_2	*air-7sp-std-06k.chm*	6000 K	1	6	V
O_2, NO, O, N, NO^+, e^-, N_2	*air-7sp-std-15k.chm* *air-7sp-gen-15k.chm*	15000 K	3	6	V
O_2, NO, O, N, NO^+, e^-, N_2	*air-7sp-std-30k.chm* *air-7sp-gen-30k.chm*	30000 K	5	6	V
O_2, OH, H_2, H_2O, N_2	*h2air-5sp-std-06k.chm* *h2air-5sp-std-15k.chm*	6000 K 15000 K	1 3	2	
O_2, H, H_2, H_2O, N_2	Not yet available				
O_2, H, H_2, H_2O, OH, O, N_2	*h2air-7sp-std-15k.chm* *h2air-7sp-gen-15k.chm* *h2air-7sp-bak-15k.chm*	15000 K	3	8	
O_2, CO_2, H_2O, NO_2, N_2	Not yet available				

[27] In Table 1, the symbol e^- is electron density, and NO^+ is ionized nitrogen oxide. Also, T_{max} is the maximum temperature at which the curve fits are valid, *Nc* is the number of thermodynamic curve fit segments, *Nr* is the number of reaction equations, and *3d* denotes Variable or Average 3rd-body efficiency.

/ — Comment lines

In the extended portion of the file, a "comment line" may be placed anywhere. This line is denoted by a / in column 1. The remainder of the line is disregarded by the input routines, as if the comment line did not exist. The purpose of this option is to allow the user to place explanatory notes within the flow condition data file. A blank line is also ignored.

COMPRESSOR FACE — Outflow boundaries, compressor face

Structured Grids

```
COMPRESSOR [FACE] {[CHUNG] mach | BOEING mode val1 [val2] | \
                   PAYNTER mach val1 val2 | SAJBEN mach angh angc} \
                  [ZONE] range1[,range2[, ...  rangen]]
```

This keyword allows an outflow boundary in a structured grid to be modeled as a compressor face. In the zone specification, the *range* parameter(s) must be one of the following forms:

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
ALL	Selects all zones

There are several models available, as described below. All are based on the observation that turbine engine conditions set the corrected mass flow, and that this corresponds directly to the average Mach number at the compressor face. These boundary conditions have been implemented mainly for the analysis of unsteady flow; however, they have also been shown to be robust for the establishment of steady-state, supercritical inlet flows.

```
COMPRESSOR [FACE] [CHUNG] mach [ZONE] range1[,range2[, ...  rangen]]
```

The CHUNG keyword option uses the Chung-Cole model (Chung and Cole, 1996). Based on the specified mass-averaged Mach number *mach*, and using the computed local Mach number and total pressure, a new local static pressure is computed.

Note: This boundary condition is identical in its effect on the flow to the DOWNSTREAM MACH keyword.

```
COMPRESSOR [FACE] BOEING mode val1 [val2] [ZONE] range1[,range2[, ...  rangen]]
```

The BOEING keyword option uses uses a model developed by Mayer and Paynter (1994). The parameters to be specified as *val1* and *val2* depend on *mode*, as shown in the following table.

mode	*val1*	*val2*
1	Average Mach number	—
2	Corrected mass flux per unit area, $\mathrm{lb_m/sec/ft^2}$	—
3	Nominal Mach number	Nominal total temperature, °R

Modes 1 and 2 are equivalent, and are useful in obtaining initial flow fields, and for simulating instantaneous changes at the compressor face via a restart. Mode 3 is used to set a constant volumetric flow condition. Typically, an initial condition is obtained using mode 1 and becomes the nominal condition. Then *val1* is set to the Mach number used in mode 1 and *val2* is set to the freestream total temperature, i.e., it is assumed that the total temperature at the compressor face is equal to the freestream value. If the average total temperature at the compressor face does not change, then modes 1 and 3 will yield identical results. However, if the average total temperature at the compressor face changes due to a freestream disturbance, for example, then the corrected flow rate will be adjusted to maintain a constant volumetric flow rate.

`COMPRESSOR [FACE] PAYNTER` *mach val1 val2* `[ZONE]` *range1* `[,`*range2* `[, ...` *rangen* `]]`

The Paynter compressor face model (Paynter, 1998) computes unsteady acoustic reflections from a compressor face subjected to acoustic and convective disturbances. This model is intended to be used for time-accurate simulations of unsteady inlet flow. The CFL number should be less than one. The flow is assumed to be subsonic and axial as it enters the compressor face.

The model assumes the compressor face is positioned within an annular duct with a hub and case, and consists of a single row of axial flow compressor blades. The conditions at the compressor face are determined by the convective velocity response coefficient α, and the acoustic response coefficient β. The definitions of α and β depend on the passage Mach number $M_{passage}$, which is given by

$$M_{passage} = M_{cf} \,/\, \cos\Gamma$$

where M_{cf} is the compressor face Mach number, and Γ is the local stagger angle.

For subsonic flow ($M_{passage} < 1$),

$$\alpha = \frac{\gamma M_{cf}^2}{1 - M_{cf}} \tan\left(\frac{\Gamma}{2}\right) \tan\Gamma$$

$$\beta = \tan^2\left(\frac{\Gamma}{2}\right) \left(\frac{1 + M_{cf}}{1 - M_{cf}}\right)$$

where γ is the specific heat ratio. For supersonic flow ($M_{passage} > 1$),

$$\alpha = \gamma M_{cf}$$

$$\beta = 1$$

Details on the implementation of this boundary condition are given by Slater and Paynter (2000).

In Wind-US, α and β may be treated as constant and specified directly, or computed using the above equations. The local stagger angle Γ is determined by assuming a linear variation between specified values of the stagger angles at the hub and case. The solidity of the blade row is assumed to be greater than one.

The absolute value of the keyword parameter *mach* sets the nominal or average compressor face Mach number M_{cf}. The meanings of *val1* and *val2* depend on the sign of *mach*:

mach	*val1*	*val2*
< 0	Stagger angle (degrees) of the compressor fan blade at the hub	Stagger angle (degrees) of the compressor fan blade at the case
> 0	Constant convective velocity response coefficient, α	Constant convective velocity response coefficient, β

`COMPRESSOR [FACE] SAJBEN` *mach angh angc* `[ZONE]` *range1* `[,`*range2* `[, ...` *rangen* `]]`

The Sajben compressor face model is basically the same as the Paynter model, except that Sajben's expression for the acoustic response coefficient is used for subsonic flow (Sajben, 1999).

Sajben's expression for the acoustic response coefficient may be written as

$$\beta = \frac{M_{cf} \tan^2\Gamma}{2(1 + M_{cf}) + M_{cf} \tan^2\Gamma}$$

where M_{cf} is the compressor face Mach number, and Γ is the local stagger angle.

With the `COMPRESSOR [FACE] SAJBEN` keyword, the keyword parameter *mach* is the nominal or average compressor face Mach number M_{cf}, and *angh* and *angc* are the stagger angles in degrees of the compressor fan blade at the hub amd case.

Examples

```
COMPRESSOR FACE CHUNG 0.3 1
COMPRESSOR FACE BOEING 1 0.3 1
COMPRESSOR FACE BOEING 2 0.5516 1
COMPRESSOR FACE BOEING 3 0.3 520.0 1
```

See Also: `DOWNSTREAM MACH`, `DOWNSTREAM PRESSURE`, `MASS FLOW`

CONVERGE — Controls convergence

Structured Grids

```
CONVERGE {LEVEL | ORDER} val
```

Unstructured Grids

```
CONVERGE LOAD [FREQUENCY ncyc] val
```

This keyword allows the user to specify the criterion used to automatically stop a run when it converges.

Note that this keyword should not be used as the sole method for determining convergence. Convergence should be monitored throughout a run by tracking residuals, integrated forces, moments, and mass flow, and/or flow variables at particular locations. See Section 6 for more detail.

Structured Grids

The options available for structured grids are:

`LEVEL` Check for maximum residual less than *val*.

`ORDER` Check for reducing maximum residual by *val* orders of magnitude.

When the specified convergence level has been reached for all zones, the calculation will stop. The default, when the `CONVERGE` keyword isn't used, is a four-order of magnitude decrease in the maximum residual.

If Newton iteration is being used, this keyword specifies the convergence criteria within a Newton time step. The overall global convergence criteria is specified using the `NEWTON` keyword.

See Also: `LOADS`, `HISTORY`, `NEWTON`, `TEST 128`

Unstructured Grids

For unstructured grids, specifying `CONVERGE LOAD` tells Wind-US to stop the calculation when the forces and moments on user-specified surfaces have leveled off within a specified tolerance. The surfaces must be defined using the `LOADS` keyword.

As part of the process, the flux dissipation and/or slope limiting parameters are adjusted in each zone to drive them to limiting values. For the Rusanov scheme, the flux dissipation and slope limiting parameters are driven to 0.1 (or lower) and 3.5 (or higher), respectively. For the Roe scheme, the slope limiting parameter is driven to 2.5 (or higher). The starting values for these smoothing parameters are normally set using the `SMOOTHING` keyword, but should be defaulted when the `CONVERGE` keyword is being used.

Convergence is checked every *ncyc* cycles, with a default of 50. The flux dissipation and/or slope limiting parameters are adjusted when the relative changes in the forces and moments on the specified surfaces within the current zone are all below the value *val*. The default for *val*, when the `CONVERGE` keyword isn't used, is 0.2.

Convergence is assumed when the flux dissipation and/or slope limiting parameters have reached their limiting values in all zones, and the maximum relative change in the forces and moments, summed over all the zones, is less than 0.01. (The convergence criterion of 0.01 may be changed using `DEBUG 24`).

See Also: `LOADS`, `SMOOTHING`, `DEBUG 24`

COUPLING — Zone coupling mode specification

Structured Grids

```
COUPLING [MODE] {CHARACTERISTIC | ROE [HIGH | LOW]}
```

This keyword controls the zone coupling algorithm used for multi-zone solutions. The two possible options are defined below.

`CHARACTERISTIC` This is NASTD's original zone coupling algorithm that uses one-dimensional characteristic flow theory to set boundary flowfield variables based on local flow direction and strength. These boundary variables are then transferred between zones using interpolation factors stored in the grid file (the *.cgd* file).

`ROE` This newer zone coupling algorithm is more consistent with Roe's flux-difference splitting scheme, which is the default explicit operator. Instead of transferring flowfield variables between zones, this algorithm transfers flux cell "interface states," which are critical quantities in Roe's scheme. In this coupling mode, the zone boundary may be thought of as a "cell interface" in Roe's scheme.

The `HIGH` option, which is the default, turns on higher-order coupling at zone boundaries. With higher-order coupling the solution derivatives are also passed between coupled zones. This results in a slight increase in memory requirements. The derivative information is used to increase the accuracy of the coupling scheme and to improve robustness at coupled boundaries through the application of a TVD operator.

Roe coupling (`HIGH` or `LOW`) requires that the Roe, Van Leer, HLLE, or Rusanov explicit operator be used. If `RHS CENTRAL` or `RHS COAKLEY` is specified, characteristic zone coupling will automatically be used.

In addition, since a TVD operator is used with higher-order Roe coupling, the default `HIGH` option cannot be used with a third-order fully upwind explicit operator, or with any of the fourth- or fifth-order explicit operators.

See Also: `RHS`, `TVD`

CROSSFLOW — Crossflow CFL factor

Structured Grids

```
CROSSFLOW [CFL] [FACTOR] val [zone_selector]
```

The CROSSFLOW keyword sets the cross-flow CFL factor to *val* in the specified zones.

For most Wind-US calculations, the time step is based on a constant CFL number throughout the flow field. Thus, for non-uniform grids, the solution advances at different rates in different parts of the grid. Because the CFL number is directly proportional to the physical time step and inversely proportional to the local grid spacing, the physical time step is small where the grid spacing is small, in order to maintain a constant CFL number. For example, in boundary layers and shear layers, where the grid is often closely packed for better resolution, the solution advances more slowly than in other parts of the flowfield. In fact, most of the iterations in a viscous solution are spent converging viscous regions.

To speed up convergence in these regions, each coordinate direction's eigenvalues are multipled by a factor before determining the time step associated with the local spacing and flow conditions. This factor varies from 1.0 when the flow is along the coordinate direction, to the specified value when the flow is perpendicular to the coordinate direction. The far-field CFL number is generally the value specified in the input data file with the CFL# keyword, but near the wall the code effectively increases the time step in the boundary layer by the specified factor. This should increase convergence of the boundary layer.

The default cross-flow CFL factor is 2.0 for three-dimensional flow, and 1.0 (i.e., no time step increase in the boundary layer) for two-dimensional flow and axisymmetric flow.

See Also: CFL#

CYCLES — Number of solution cycles

```
CYCLES ncyc [PRINT [FREQUENCY] freq]
```

This keyword is used to set the number of cycles *ncyc*, and is required in the input data file. By default each cycle has five flowfield iterations in all zones, but this may be changed using the `ITERATIONS` keyword.

Cycle time information will be written to the *.lis* file every *freq* cycles, starting with the first cycle. The default is every cycle.

For structured grids, residuals will also be written to the *.lis* file every *freq* cycles, starting with the first cycle, but only for iterations consistent with the `PRINT FREQUENCY` specified with the `ITERATIONS` keyword. For unstructured grids, residuals will be written to the <i>.lis</i> file every cycle.

Note that this does not affect integrated properties specified using the `LOADS` keyword block. The print frequency for integrated properties is controlled by the `PRINT` keyword in the `LOADS` keyword block.

Example

If the user specifies

```
CYCLES 1000 PRINT FREQUENCY 10
ITERATIONS PER CYCLE 10 PRINT FREQUENCY 10
```

cycle time information will be printed for cycles 1, 11, 21, etc. For structured grids, residuals will only be printed for iterations 10 (in cycle 1), 110 (cycle 11), 210 (cycle 21), etc.

See Also: `ITERATIONS`, `LOADS`

DEBUG — Developer debug options

Unstructured Grids

```
DEBUG number [mode]
```

This keyword is intended for use during code development and testing. The various debug options and modes are described in Table 2. For each option, the subroutines referencing that option are listed in parentheses. If *mode* is not described for a given debug option, it should be set to 1 to activate that option. If *mode* is omitted, a default value of 1 is used.

Unless noted otherwise, this keyword only applies to unstructured grids.

Table 2: Developer Debug Options

number	**Description**
1	Generate grid and solution files for post-processing by Ensight (`PreHybrid, lpgrpHybrid`)
2	Compute wall distance and save in *.cfl* file as the variable `WallD` (`WallDistance`)
3	Output convergence history in ICAT format (`Explicit, Implicit100, Implicit110, Implicit210, Residue, TimeStep, TimeStep_Pre`)
4	Write skin friction file, containing columns for x, y, z, C_f, u^+, and y^+, and heat transfer file, containing columns for$x$, y, z, C_h, T, and p. C_h will be dimensional if *mode* = 1, and non-dimensional if *mode* = 2. (`AdiabaticWall, IsoThermalWall`)
5	Write `RtMin` and `RtMax`, the minimum and maximum values of the turbulence dependent variable, into the *.lis* file (`Update, UpdateCellQn`)
6	Write the number of points that were switched from second-order to first-order accurate, due to the density/pressure/energy range (`nBad`) and/or due to the grid angle between two neighboring cells (`nBadGrd`), into the *.lis* file (`IntrrFlux, IntrrFluxFRC, IntrrFluxNthlp, SelfCoupled, Update, UpdateCellQn, ZnlIntrFace, ZnlNthlp`)
7	Write the zonal maximum and minimum values of the dependent variables, and the maximum and minimum vertex value of the pressure, into the *.lis* file (`InitSmooth, Qcell2Qvrtx`)
8	Split the edge data (*.cge*) file into *mode* files (`edgopn`)
9	Write extra arrays containing cell volume, cell centroid coordinates, face center coordinates, and cell connectivity into the *.cge* file for debugging purposes (`edgopn, PreHybridRead, PreHybridWrite`)
10	Write detailed grid information and wall distance into the *.lis* file (`CheckPreInfo1, PreHybrid, PreHybridWrite, WallDistance`)
11	Change reference conditions for frozen chemistry calculations to be the same as in ICAT (`sichemHybrid, sinsHybrid`)
12	If the Mach number is > 2.0, use normal shock relations to get the initial surface density and pressure (`AdiabaticWall`)

Continued on next page

Table 4: Developer Debug Options (*Continued*)

number	Description
13	Smooth initial and restart conditions, using *mode* smoothing passes (`InitSmooth, lpgrpHybrid`)
14	Use superbee slope limiting; recommended for heat transfer calculations (`Implicit100, Implicit110, Implicit210`)
15	Use alternate method for computing gradients of dependent variables (`AdiabaticWall, ArbitraryInFlow, BlasiusOutFlow, Charact421, Characteristics, Extrapolate, FreeStream, IntrrFlux, IntrrFluxFRC, IntrrFluxNthlp, IsoThermalWall, MassFlux, PlaneOfSymmetry, Resv405, SelfCoupled, SubsonicInFlow, SubsonicOutFlow, Ttotalmdot, ZnlIntrFace, ZnlNthlp`)
16	For multi-species flows, write thermodynamic data table into the file *Thermo_Tables*. This option applies to both structured and unstructured grids. (`propin`)
18	Include the diagonal viscous flux Jacobian terms; important for $y^+ < 0.5$ (`BndryFlxJcbian, Implicit110, Jacobian110, Relax100, Relax100_Pre`)
19	Use enthalpy preserving scheme (`Implicit100, Implicit110, Implicit210, ZnlIntrFace`)
20	Cell volume is computed by dividing the cell into tetrahedra. For *mode* = 1, when the volume of any of the tetrahedra is < 0.0, the cell volume is computed as the product of the mean area of the triangular faces and the perpendicular distance between them. (`PreHybrid, PreHybridRead, prism`)
21	When computing residuals and limiting the change in dependent variables, nondimensionalize by freestream values instead of max values, for compatibility with ICAT (`Residue`)
22	?? (`loadqbc`)
23	If the flux dissipation parameter (see the SMOOTHING keyword) is < 1.0, locally increase it to 1.0 when pressure difference between the left and right states is large. (`LaxFriedrichs, Lax_Pre`) *mode* Result 0 No modification to the flux dissipation parameter < 0 Modify the flux dissipation parameter when the pressure difference is greater than 30% > 0 Modify the flux dissipation parameter when the pressure difference is is greater than *mode*%
24	The convergence criterion (see the CONVERGE keyword) is set to 1./*mode*. The default convergence criterion is 0.01. (`LoadCnvrg`)
25	Apply slope limiting at zonal boundaries (`Implicit100, Implicit110, Implicit210`)
26	Apply slope limiting to temperature (`SlopeLimit`)

Continued on next page

Table 4: **Developer Debug Options** (*Continued*)

number	Description
27	When checking for "bad" pressure values, for ideal gases and equilibrium air set the maximum allowed temperature to the minimum of $\gamma p_{max}/\rho_{min}$ and twice the freestream total temperature, where the values of p_{max} and ρ_{min} are set by the Q LIMIT keyword. (Update)
28	Update dependent variables using the formula $Q_{n+1} = Q_n + \omega \Delta Q$, where $\omega = mode/100$. The default value for ω is 1.0 for ideal gases and equilibrium air, and 0.75 for frozen or finite rate chemistry. (Update)
29	Limit eigenvalues in subroutine Roe to a maximum value of idebug(29) × (face area)/100 (Roe)
30	For Euler flows, use a no-slip boundary condition at boundaries labeled as "viscous walls" (AdiabaticWall, IsoThermalWall)
31	Don't stop execution in CheckPreInfo1 when errors are found in cell volumes or face normals (CheckPreInfo1)
32	When using the Rusanov (Lax-Friedrichs) scheme, limit the production term in the Spalart-Allmaras turbulence model. If *mode* > 0, it specifies the maximum allowed ratio of production to dissipation. If *mode* < 0, the maximum allowed ratio is set to 10. (Spalart_Allmaras)
33	Don't apply limiting for coupled boundary condition. The limiting is most needed when high-order coupling is used between structured and unstructured zones. (ZnlIntrFace)
34	Don't apply flux limiting to the calculation of interior fluxes in unstructured grids. (IntrrFlux)
35	When EXTRAPOLATE is not used with the DOWNSTREAM PRESSURE keyword, use the specified pressure at supersonic outflow boundaries instead of extrapolating. (The default is to extrapolate conditions at supersonic outflow boundaries, whether or not EXTRAPOLATE is used.) (OutFlow)
36	For specified pressure at outflow boundaries (the DOWNSTREAM PRESSURE keyword) apply the pressure immediately, without under-relaxation. (OutFlow)
37	For specified mass flow at outflow boundaries (the MASS FLOW keyword) apply the associated pressure immediately, without under-relaxation. (MassFlux)
38	For specified mass flow at arbitrary inflow boundaries (USURFACE MASS in the ARBITRARY INFLOW keyword block) don't exit if the flow at the boundary becomes supersonic. (ArbitraryInFlowMass)
65	Write log of memory allocation/deallocation to the file *memdebug.lis* (MemDebug)

DOWNSTREAM MACH — Outflow boundaries, Mach number

Structured Grids

```
DOWNSTREAM MACH [NUMBER] mach [ZONE] range1[,range2[, ...  rangen]]
```

This keyword allows the specification of a mass-averaged subsonic Mach number *mach* at outflow boundaries in structured grids. Based on the specified mass-averaged Mach number, and using the computed local Mach number and total pressure, a new local static pressure is computed. This boundary condition simulates the uniform Mach number characteristics observed at the compressor faces of turbine engines, and is identical in its effect on the flow to the `COMPRESSOR FACE CHUNG` keyword.

In the zone specification, the *range* parameter(s) must be one of the following forms:

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
`ALL`	Selects all zones

See Also: `COMPRESSOR FACE`, `DOWNSTREAM PRESSURE`, `MASS FLOW`

DOWNSTREAM PRESSURE — Outflow boundaries, pressure

Structured Grids

```
DOWNSTREAM PRESSURE { \
   value [EXTRAPOLATE [SUPERSONIC]] | \
   FREESTREAM [EXTRAPOLATE [SUPERSONIC]] | \
   EXTRAPOLATE [ALWAYS] | \
   value VARIABLE i j k [RELAXER rlxr] | \
   value UNSTEADY {SINUSOIDAL | USERSPEC} Δp freq phase \
   } [ORDER {ZERO|0|ONE|1}] [ZONE] range1[,range2[, ...  rangen]]
```

Unstructured Grids

```
DOWNSTREAM PRESSURE { \
   value [EXTRAPOLATE [SUPERSONIC]] | \
   FREESTREAM [EXTRAPOLATE [SUPERSONIC]] | \
   EXTRAPOLATE [ALWAYS] \
   } [ZONE] range1[,range2[, ...  rangen]]
```

This keyword controls the specification of a pressure boundary condition at outflow boundaries. In the zone specification, the *range* parameter(s) must be one of the following forms:

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
ALL	Selects all zones

Structured Grids

There are five possible modes for structured grids, defined as follows:

```
DOWNSTREAM PRESSURE value [EXTRAPOLATE [SUPERSONIC]] \
   [ORDER {ZERO|0|ONE|1}] [ZONE] range1[,range2[, ...  rangen]]
```

This mode specifies the pressure *value* (in psi) to be applied at the outflow boundary in the specified zone(s). The EXTRAPOLATE [SUPERSONIC] option tells Wind-US to extrapolate all flow conditions to the boundary for points where the flow is supersonic. Either zeroth- or first-order extrapolation will be used, as specified by ORDER.

For boundary points where the flow is subsonic,

1. The pressure at the boundary is set to the user-specified value.
2. For each boundary point, the density and momentum, plus the effective gamma, compressibility factor, and speed of sound, are extrapolated from the interior to the boundary using either zeroth- or first-order extrapolation, as specified.
3. The energy at each boundary point is computed, consistent with the user-specified pressure and the extrapolated values of density, etc.

```
DOWNSTREAM PRESSURE FREESTREAM [EXTRAPOLATE [SUPERSONIC]] \
   [ORDER {ZERO|0|ONE|1}] [ZONE] range1 [,range2 [, ...  rangen]]
```

This mode is the same as the previous one, except that the pressure value is taken from the FREESTREAM keyword.

```
DOWNSTREAM PRESSURE EXTRAPOLATE [ALWAYS] \
   [ORDER {ZERO|0|ONE|1}] [ZONE] range1 [,range2 [, ...  rangen]]
```

This mode extrapolates all flow conditions for all points on the boundary, regardless of whether or not the flow there is supersonic.

```
DOWNSTREAM PRESSURE value VARIABLE i j k [RELAXER rlxr] \
   [ORDER {ZERO|0|ONE|1}] [ZONE] range1 [,range2 [, ...  rangen]]
```

This mode imposes the pressure *value* (in psi) only at the specified (*i,j,k*) boundary point in the specified zone(s). The indices (*i,j,k*) should correspond to a point on the outflow boundary, although at present no check is made to verify that they do. The pressure at the remaining boundary points will spatially vary according to the spatial variation of pressure at the solution points adjacent to the boundary, and may be over- or under-relaxed using the input relaxation factor *rlxr*. The default value for *rlxr* is 1.0 (i.e., no relaxation).

The procedure is as follows:

1. A "reference" pressure p_{ref} at the specified (i,j,k) boundary point is found by extrapolating the interior pressure values to the boundary, using either zeroth- or first-order extrapolation, as specified.
2. For each boundary point, the density and momentum, plus the pressure, effective gamma, compressibility factor, and speed of sound, are extrapolated from the interior to the boundary using either zeroth- or first-order extrapolation, as specified.
3. At each boundary point, the pressure is re-computed using

   $$p = p_{ext} \frac{p_{nom}}{p_{ref}}$$

   where p_{ext} is the extrapolated value from step 2, p_{nom} is the nominal value specified with the DOWNSTREAM PRESSURE keyword, and p_{ref} is the "reference" value from step 1.
4. The actual imposed pressure at each point is relaxed using

   $$p = rp + (1 - r)p_{old}$$

   where r is the input relaxation factor *rlxr*, and p_{old} is the pressure value from the previous iteration.
5. The energy at each boundary point is computed, consistent with the pressure value from step 4, and the extrapolated values of density, etc., from step 2.

```
DOWNSTREAM PRESSURE value UNSTEADY \
   {SINUSOIDAL | USERSPEC} Δp freq phase \
   [ORDER {ZERO|0|ONE|1}] [ZONE] range1 [,range2 [, ...  rangen]]
```

This mode allows an unsteady pressure to be applied at the outflow boundary in the specified zone(s). A sinusoidal or user-defined oscillation may be specified. The parameters are defined as:

value	Baseline pressure, p_s (psi)
Δp	Amplitude of oscillation (psi)
freq	Frequency of oscillation, ω (Hz)
phase	Phase angle of oscillation, ϕ (deg)

If `SINUSOIDAL` is used, specifying a sinusoidal pressure oscillation, the pressure is computed from

$$p = p_s + \Delta p \, \sin[2\pi(\omega t + \phi)]$$

where p is the pressure and t is the time.

If `USERSPEC` is used, specifying a user-defined pressure oscillation, a table must be input immediately following the `DOWNSTREAM PRESSURE` keyword, with the following format:

```
PROFILE npts
per(1)     amp(1)
per(2)     amp(2)
...
per(npts) amp(npts)
```

where *npts* is the number of points in the profile (max 65), *per* is the normalized period (i.e., from 0.0 to 1.0), and *amp* is the normalized amplitude (i.e., from −1.0 to 1.0). As an example, the following normalized pressure oscillation:

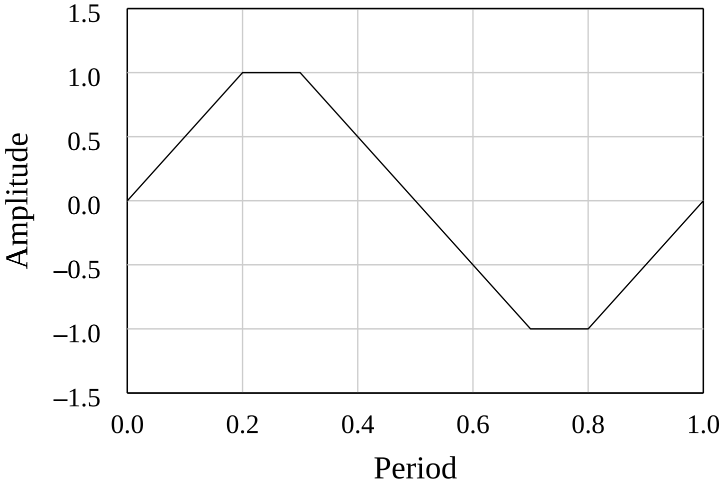


Figure 7: Example user-specified unsteady pressure oscillation

could be specified using the following profile input:

```
PROFILE 6
0.0   0.0
```

```
0.2   1.0
0.3   1.0
0.7  -1.0
0.8  -1.0
1.0   0.0
```

Once the downstream pressure is determined for the current time level, the density and momentum at each boundary point, plus the effective gamma, compressibility factor, and speed of sound, are extrapolated from the interior to the boundary using either zeroth- or first-order extrapolation, as specified. The energy at each boundary point is then computed, consistent with the pressure and the extrapolated values of density, etc.

Extrapolation Notes

The default for all extrapolation is zeroth-order (i.e., conditions at the boundary are set to the values at the computational plane adjacent to the boundary). This results in a discontinuous slope in flow values near the outflow boundary, which may be important for flows with significant streamwise pressure gradients. First-order extrapolation yields smoother results.

For flows with little or no streamwise pressure gradient near the outflow boundary, the results using zeroth- and first-order extrapolation are essentially identical. Convergence rates and the final residual values are generally better with zeroth-order extrapolation, however, so the default zeroth-order extrapolation is recommended.

For flows with significant streamwise pressure gradients near outflow boundaries, zeroth-order extrapolation can give poor results at the outflow boundary, and in some cases these can affect values at the inflow boundary. First-order extrapolation is thus recommended for these flows.

See Also: `COMPRESSOR FACE`, `DOWNSTREAM MACH`, `MASS FLOW`, `FREESTREAM`

Unstructured Grids

There are three possible modes for unstructured grids, defined as follows:

```
DOWNSTREAM PRESSURE value [EXTRAPOLATE [SUPERSONIC]] \
   [ZONE] range1 [,range2 [, ...  rangen]]
```

This mode specifies the pressure *value* to be applied at the outflow boundary in the specified zone(s). The application of the specified pressure is under-relaxed to prevent large differences in pressure from occuring in the first iteration. `DEBUG` option 36 may be used to apply the specified pressure immediately, without under-relaxation.

The `EXTRAPOLATE [SUPERSONIC]` option tells Wind-US to extrapolate all flow conditions to the boundary for points where the flow is supersonic.[28] For unstructured grids, only zeroth-order extrapolation is available.

```
DOWNSTREAM PRESSURE FREESTREAM [EXTRAPOLATE [SUPERSONIC]] \
   [ZONE] range1 [,range2 [, ...  rangen]]
```

This mode is the same as the previous one, except that the pressure value is taken from the `FREESTREAM` keyword.

[28] Actually, for supersonic outflow, conditions are extrapolated by default, whether `EXTRAPOLATE [SUPERSONIC]` is specified or not. This may be over-ridden using `DEBUG` option 35.

```
DOWNSTREAM PRESSURE EXTRAPOLATE [ALWAYS] \
   [ZONE] range1 [,range2 [, ...  rangen]]
```

This mode extrapolates all flow conditions for all points on the boundary, regardless of whether or not the flow there is supersonic.

See Also: MASS FLOW, FREESTREAM, DEBUG 35, DEBUG 36

DQ — ΔQ limiter

Structured Grids

```
DQ [LIMITER] [OFF | [ON | NXAIR] [DRMAX drmax] [DTMAX dtmax]]
```

Unstructured Grids

```
DQ [LIMITER] [OFF | ON [DEMIN demin] [DEMAX demax] [DQRATIO dqratio]]
```

This keyword may be used to limit the change in the solution over a single iteration. This may be helpful, especially in the initial stages of a calculation, in maintaining stability, and allow the use of larger CFL numbers than might otherwise be possible.

Structured Grids

For structured grid zones, the keyword limits the change in density and/or temperature over a single iteration.

`OFF` Don't limit the change in density or temperature.

`ON` Use the MacCormack **ΔQ** limiter (MacCormack, 1997). With this limiter, the entire solution, including the turbulence variables, is limited throughout the zone, such that the specified fractional changes in density and temperature are not exceeded. (See below for some further considerations when multiple subiterations are being used.)

`NXAIR` Use the **ΔQ** limiter from the NXAIR code. This limiter acts locally; the solution is limited only at those points that exceed the specified fractional changes in density or temperature. Unlike the MacCormack limiter, the NXAIR limiter is not applied to the turbulence model equations (although the models of course use the limited Navier-Stokes variables, so there is an indirect influence).

The NXAIR limiter assumes a perfect gas when limiting the temperature. The solution will be aborted if it is specified for flows with multiple species.

`DRMAX` *drmax* *drmax* specifies the fractional change allowed in the density over an iteration. I.e., specifying "`DQ LIMITER ON DRMAX 0.2`" means the density will not be permitted to change by more than ±20% from one iteration to the next.

`DTMAX` *dtmax* *dtmax* specifies the fractional change allowed in the temperature over an iteration.

The default, when `DQ LIMITER` is not used, is to not limit the change in density or temperature. If just `DQ LIMITER` is specified, the MacCormack **ΔQ** limiter is used. The defaults for *drmax* and *dtmax* are both 0.5. Thus, if just "`DQ LIMITER ON`" is specified, both density and temperature will be allowed to change by no more than ±50% over an iteration.

The use of the `DQ LIMITER ON` keyword becomes somewhat problematic when multiple subiterations are used for the Navier-Stokes equations (using the `NAVIER-STOKES ITERATIONS` keyword) and/or the turbulence model equations (using the ITERATIONS option with the TURBULENCE keyword). By default, the number of sub-iterations for both the Navier-Stokes and turbulence model equations is one. In this case, each iteration for the Navier-Stokes equations is followed by an iteration for the turbulence model equations, and if the limiter is applied to the Navier-Stokes solution, it is also applied to the turbulence model solution.

If the number of Navier-Stokes sub-iterations is one, and if multiple sub-iterations are used for the turbulence model equations, then if the limiter is applied to the Navier-Stokes solution, it is applied to each turbulence model sub-iteration.

Also, if multiple Navier-Stokes sub-iterations are used, it's possible that the computed flow field is such that the limiter is applied during some sub-iterations, but not others. In this case, if the limiter is applied during the final Navier-Stokes sub-iteration, it is again applied to each turbulence model sub-iteration. If the limiter is not applied during the final Navier-Stokes sub-iteration, it will not be applied at all during the turbulence model iteration.

For these reasons, it is recommended that the number of sub-iterations for the Navier-Stokes and turbulence model equations be left at their default values of one when the DQ LIMITER ON keyword is used.

Unstructured Grids

For unstructured grid zones, the keyword limits the change in density and/or temperature over a single iteration.

```
DQ [LIMITER] [OFF | ON [DEMIN demin] [DEMAX demax] [DQRATIO dqratio]]
```

TFor unstructured grid zones, the keyword limits the change in energy over a single iteration. It also may be used to set the change allowed in the density at inviscid walls.

OFF — Don't change the default limits. Note that for unstructured grids, DQ LIMITER OFF doesn't mean "turn the limiter off". The default limits are still applied.

ON — Change the default limits.

DEMIN *demin* — *demin* specifies the fractional decrease allowed in the energy over an iteration, and must be a negative value. I.e., specifying "DQ LIMITER ON DEMIN -0.2" means the energy will not be permitted to decrease by more than 20one iteration to the next.

DEMAX *demax* — *demax* specifies the fractional increase allowed in the energy over an iteration, and must be a positive value.

DQRATIO *dqratio* — *dqratio* specifies the fractional change allowed in the density over an iteration at inviscid walls.

Note that for unstructured grids, the limiter cannot be turned off. The entire solution, including the turbulence variables, is limited throughout the zone, such that the specified (or default) fractional increase or decrease in energy is not exceeded. And at inviscid walls, the change in density is not allowed to exceed the specified (or default) limit.

The default values for *demin*, *demax*, and *dqratio* are −0.5, 2.0, and 10.0, respectively.

See Also: Q LIMIT

END — Termination

```
[END]
```

This keyword, which must begin in column 1, may be used to end the input data file.

ENTROPY FIX — Entropy fix for Roe scheme

Structured Grids

```
ENTROPY [FIX] [ON|OFF]
```

When the Roe scheme is being used, this keyword may be used to turn on a partial “entropy fix”, intended to help prevent expansion shocks by not allowing the flow eigenvalues to have non-physical values.

If this keyword is not used, no entropy fix is applied (i.e., the same as `ENTROPY FIX OFF`). If this keyword is used, but without specifying `ON` or `OFF`, the fix is turned on (i.e., the same as `ENTROPY FIX ON`).

See Also: `RHS`

FIXER — Instability smoothing

Structured Grids

```
FIXER [PRINT] [zone_selector]
```

Wind-US's `FIXER` capability searches for computational points at which there are negative values of density or internal energy (due to numerical instabilities) and replaces the faulty values with averages from nearby j and k points in the same i-plane. (I.e. the smoothing is two-dimensional; values from adjacent i-planes are not used.) The process is iterative, with multiple smoothing passes. Only "active" points are examined, not wall, coupled boundary, hole, or fringe points.

In a given i-plane, if more than 50% of the points are "bad", or if the smoothing process fails to remove all the negative values, the run is aborted.

Using `FIXER` may help the solution through difficult transients, but *it may also simply smear out instabilities over a larger portion of the flowfield.* You should maintain a careful watch over the solution.

For each i-plane containing negative values of density or internal energy, the zone, iteration number, i index, and number of bad points will be written to the list output (*.lis*) file. If the `PRINT` option is specified, the listing will also include the j and k indices of each bad point.

FREESTREAM — Freestream conditions

```
FREESTREAM {STATIC | TOTAL} [CONDITIONS] M P T α β
```

This keyword allows input of freestream flow conditions. The user-specified parameters are defined as:

M Mach number

P Static or total pressure (psi), depending on the `STATIC | TOTAL` keyword

T Static or total temperature (°R), depending on the `STATIC | TOTAL` keyword

α, β Angles of attack and yaw (degrees)

Note that, if U is the freestream velocity magnitude, α and β are related to the Cartesian velocity components by:

$$\begin{aligned} w &= U \sin\beta \\ u &= U \cos\beta \cos\alpha \\ v &= U \cos\beta \sin\alpha \end{aligned}$$

Note: The local flow angles (*localpha* and *locbeta* in the CFPOST post-processing package) are defined relative to the x, y, z coordinates and are given by:

$$\begin{aligned} \textit{localpha} &= \tan^{-1}(v/u) \\ \textit{locbeta} &= \tan^{-1}(w/u) \end{aligned}$$

Thus if β is not equal to 0, *locbeta* is not equal to β.

Note: Wind-US assumes α is rotation about the z axis. That is, y is up.

See Also: `INITIALIZE`, `REINITIALIZE`

FRINGE — Solution mode at fringe points

Structured Grids

```
FRINGE [MODE] FROZEN [zone_selector]
```

For overlapping structured zonal boundaries, this keyword may be used to freeze the solution at fringe points during a cycle. Solution values at these points are then updated at the end of the cycle.

`FRINGE FROZEN` *must* be used for double-fringe boundaries. Running a double-fringe grid without this keyword may lead to erroneous results.

`FRINGE FROZEN` may also be specified for single-fringe boundaries, but is not required. The default for single-fringe boundaries is to update the solution at fringe points every iteration.

Using double fringes increases the solution accuracy at overlapping boundaries. Note, though, that by freezing the solution over a cycle, the solution at fringe points will lag in time behind the solution at interior points. This could potentially lead to instabilities during transients, or a reduction in the convergence rate if a large number of iterations per cycle are specified. However, testing on a limited number of cases has not revealed any problems when using up to five iterations per cycle.

Double-fringe boundaries may be created with GMAN, by first selecting double-fringe mode using (in GMAN's graphical mode) `MODIFY BNDY > GENERATE FRINGE > SET FRINGE-MOD > DOUBLE FRINGE`, then generating the fringe.

GAS — Gas property specification

```
GAS gam prl prt gasc
```

This option allows the user to input different values of γ, laminar and turbulent Prandtl numbers, and gas constant. The parameters are defined as:

gam Ratio of specific heats $\gamma = c_p/c_v$ (default is 1.4)

prl Laminar Prandtl number (default is 0.72)

prt Turbulent Prandtl number (default is 0.90)

gasc Gas constant R (default is 1716 $\mathrm{ft}^2/\mathrm{sec}^2$-°R)

Note: The ARBITRARY INFLOW keyword block, if used, must come after the GAS keyword in the input data (*.dat*) file.

GRAVITY — Add gravity body forces

Structured Grids

GRAVITY x_c y_c z_c g_x g_y g_z

The GRAVITY keyword allows the user to include the effects of gravity on the fluid.

x_c, y_c, z_c Coordinates of a point on the "ground" plane (normal to the gravity vector) used to define the location of zero potential energy, in grid units

g_x, g_y, g_z Components of the gravity vector, in ft/sec^2. For example, if the y direction is normal to the earth's surface, these values might be 0.0, -32.2, 0.0.

GRID LIMITER — Grid limiting capability

```
GRID LIMITER {ANGLE angle | OFF} [zone_selector]
```

Wind-US's grid limiting capability switches the explicit operator to a first-order scheme in the presence of grid turning greater than a specified amount. This capability may be needed to reduce numerical instabilities near wing tips, leading edges, and other geometric features which may require extreme amounts of grid turning.

The parameter *angle* is the number of degrees off of a straight line allowed before limiting the scheme to first order.

See Also: `TEST 110`, `TVD`

HISTORY — Time history flowfield variable tracking

Structured Grids

```
HISTORY
   VARIABLE [M] [p] [T] [u] [v] [w] [radius] [DeltaP] [x] [y] [z] \
            [rho] [rho*u] [rho*v] ...
   [FREQUENCY f]
   REGION nzn ibeg iend jbeg jend kbeg kend
   REGION nzn {NODE | CELL} num
   ...
ENDHISTORY ...
```

For unsteady flow problems, the `HISTORY` keyword block allows the user to track the temporal evolution of variables at discrete specified points. The specified flow quantities are written to a common time history (*.cth*) file every *f* iterations. Upon completion of a time history run, the auxiliary program *thplt* may be used to analyze the data and/or to create a GENPLOT file that may then be plotted using CFPOST.[29] The *.cth* file contains reference and scaling data. Thus, when *thplt* is used to create a GENPLOT file, the time history variables will be dimensional.

For the results to be strictly valid, all zones must run with the same time step and with one iteration per cycle. However, in recognition that this is not always feasible, this capability can be used with only the stipulation that the zone(s) in which temporal evolution information is desired be run with a constant time step.

The *.cth* file itself does not support direct I/O. Therefore, when Wind-US is being run in parallel mode, each individual processor maintains the requested time history for its zones, but calls the master process to update the *.cth* file whenever the flow (*.cfl*) file is updated, and whenever the time history memory buffer is filled. This forces the *.cth* file to be consistent with the *.cfl* file.

When restarting a time-accurate job with the same input conditions, the existing *.cth* file will normally be extended. However, any changes to the time history points or variables, or the flow reference state, will require starting with a fresh *.cth* file. In this case, the name of the previous *.cth* file should be changed. If time history or reference condition changes have been made, and an older *.cth* file exists with the same base name, the Wind-US run will abort. In any case, *thplt*, the time history post-processing tool, can read multiple *.cth* files to combine the different time intervals.

The various elements of the `HISTORY` keyword block are defined as follows:

```
HISTORY
```

Defines the beginning of the `HISTORY` block

```
VARIABLE [M] [p] [T] [u] [v] [w] [radius] [DeltaP] [x] [y] [z] \
         [rho] [rho*u] [rho*v] ...
```

Specifies the variables to be recorded. At least one must be specified, and the variable names are *case-sensitive*. The first eight variables shown above are defined as follows:

[29] Because of changes to the format of the *.cth* file, the *timplt* utility used to analyze *.cth* files created by WIND 5.51 and earlier will not work with *.cth* files created by the current Wind-US code.

`M`	Mach number
`p`	Static pressure
`T`	Static temperature
`u`	Velocity in the x direction
`v`	Velocity in the y direction
`w`	Velocity in the z direction
`radius`	Distance from a specified reference point to the location of a shock front. See the section Front Tracking Mode for details.
`DeltaP`	Monotone pressure rise across the shock front. See the section Front Tracking Mode for details.

In addition to the variables listed above, any variable in the `q` array may be specified. These of course depend on the equations being solved. The possible `q` variables are listed in Table 3, in groups, along with an indication of when they are available.

Table 3: `HISTORY` Keyword — `q` Variables

Name	Definition	When Used
—*Navier-Stokes equations*		
`rho`	Static density	Always
`rho*u`	Momentum in the x direction	
`rho*v`	Momentum in the y direction	
`rho*w`	Momentum in the z direction	
`rho*e0`	Total energy	
—*Auxiliary parameters*		
`beta`	Effective specific heat ratio	Always
`Z`	Compressibility factor	
`a`	Speed of sound	
`kappa`	Thermal conductivity	
`dt`	Time step	
—*Viscosity*		
`mul`	Laminar viscosity coefficient	Viscous flows
`mut`	Turbulent viscosity coefficient	
—*Turbulence equations*		
`anut`	Eddy viscosity	Baldwin-Barth and Spalart-Allmaras turbulence models
`k`	Turbulent kinetic energy	SST and Chien k-ϵ turbulence models
`omega`	Specific dissipation rate	SST turbulence model
`epsilon`	Turbulent dissipation	Chien k-ϵ turbulence model

Continued on next page

Table 3: HISTORY Keyword — q Variables (*Continued*)

Name	Definition	When Used
—*Chemistry equations*		
species	Mass fraction of *species*, where *species* is the species name defined in the chemistry data file (see Section 7.9 and the CHEMISTRY keyword block)	Non-reacting chemistry
rho**species*		Finite-rate reacting chemistry
shf	Specific heat of formation	Chemistry
—*Navier-Stokes equations in rotating frame*		
rho*ur	Momentum in the x direction in a rotating reference frame (rho*u, etc., are in the inertial frame)	Rotating reference frame
rho*vr	Momentum in the y direction in a rotating reference frame	
rho*wr	Momentum in the z direction in a rotating reference frame	
rho*e0r	Total energy in a rotating reference frame	
—*MFD equations*		
Bx, By, Bz	Magnetic field components in the x, y, and z directions	MFD flows
Ex, Ey, Ez	Electric field components in the x, y, and z directions	
Jx, Jy, Jz	Current density components in the x, y, and z directions	
Lx, Ly, Lz	Lorentz force components in the x, y, and z directions	
sigma	Conductivity	
voltage	Voltage	

```
FREQUENCY f
```

Specifies the number of solver iterations between output of time history information. The default is to write to the *.cth* file every 10 iterations.

```
REGION nzn ibeg iend jbeg jend kbeg kend
REGION nzn {NODE | CELL} num
...
```

Defines the discrete locations where temporal information will be sampled in zone *nzn*. The different formats correspond to a structured zone range, and a particular node or cell in an unstructured node-based or cell-based scheme.[30]

[30] Note, though, that Wind-US does not yet support the use of the HISTORY keyword with unstructured grids.

Except for the special-purpose variables `radius` and `DeltaP`, in a structured grid time history data will be recorded at each point in the domain defined by the indices (*ibeg,jbeg,kbeg*) to (*iend,jend,kend*). The variables `radius` and `DeltaP` are intended for use in tracking the location of a shock wave. In this case, the `REGION` parameters are defined differently. See the section Front Tracking Mode for details.

Multiple `REGION` lines may be used to specify multiple sampling regions, in the same zone, or different zones. Grid sequencing is supported for structured grids, but there is presently no other way (except multiple `REGION` lines) to spatially sub-sample a region.

```
ENDHISTORY
```

Defines the end of the `HISTORY` block.

Front Tracking Mode

For structured grids, a special mode exists that can be useful for tracking the motion of shock waves. If the region is specified as:

`REGION` *nzn i0 idir j0 jdir k0 kdir*

where one of *idir*, *jdir*, *kdir* is ±1 and the other two are zero, then front tracking mode is active in zone *nzn*.

Beginning at the point (*i0,j0,k0*), the solution is sampled to the end of the zone in the specified direction, looking for the maximum change in pressure across a cell. This location is then used as the "probe location" to output the specified variables. In this context, the `radius` variable represents the distance of this point from the point (*i0,j0,k0*). Note that this is probably the only time that a time history variable of x, y, or z makes sense, as they can be used to more precisely specify the location of the detected front.

To provide an indication of the evolution of the shock strength, the variable `DeltaP` can be used. When this variable is specified, the search is continued from the detected front location to the end of the zone, in the specified search direction, and the maximum monotone pressure change is recorded.

Example 1

The following use of the `HISTORY` block will create a time history (*.cth*) file containing the static pressure at the points (17,1,1), (17,11,5), and (9,11,7) in zones 1, 2, and 3, respectively. Values will be written to the file every ten iterations.

```
History
   Variable p
   Region 1 17 17  1  1 1 1
   Region 2 17 17 11 11 5 5
   Region 3  9  9 11 11 7 7
Endhistory
```

Example 2

In the following example, the Mach number and pressure will be recorded in zone 5, for the grid points (i, j, k) = (7–16,22–24,19). Values will be written to the file every five iterations.

```
History
   Variable M p
   Frequency 5
```

```
      Region 5 7 16 22 24 19 19
   Endhistory
```

Example 3

In this example, the position and strength of a shock wave will be tracked in the $+i$ direction in zone 4. The point (1,52,20) will be used as the reference point, and values will be recorded every 20 iterations.

```
   History
      Variable radius x DeltaP
      Frequency 20
      Region 4 1 1 52 0 20 0
   Endhistory
```

HLLE | RUSANOV — Anti-diffusion terms for HLLE and Rusanov schemes

Structured Grids

```
{HLLE | RUSANOV} EPSS epss [zone_selector]
```

This keyword allows the user to control the behavior of the anti-diffusion term in the HLLE and Rusanov schemes for structured grids. The parameter *epss* is used in the computation of a switch used to regulate the anti-diffusion terms. The possible values for *epss* are shown below.

epss	Switch	Result
0.0	1.0	Anti-diffusion terms are always fully on.
> 0.0	$1.0 - epss \lvert p_{scal} \rvert$	Anti-diffusion terms are on, scaled by the absolute value of a pressure gradient scaling parameter p_{scal}, with *epss* as a coefficient. The result is that the anti-diffusion terms are smaller in regions where the pressure gradient is changing rapidly. Larger values of *epss* result in smaller anti-diffusion terms. The switch is limited to a minimum value of 0.0 (fully off).
< 0.0	$1.0 + epss$	Anti-diffusion terms are on, with the switch hard-wired to the indicated value. Larger negative values of *epss* result in smaller anti-diffusion terms. The switch is limited to a mimimum value of 0.0 (fully off), which corresponds to $epss = -1.0$.

The default value for *epss* is 0.0 for the HLLE scheme, and 0.5 for the Rusanov scheme.

See Also: RHS

HOLD — Hold conditions at freestream inflow boundaries

```
HOLD {TOTALS | CHARACTERISTICS} [zone_selector]
```

Specifying HOLD TOTALS indicates that total conditions are to be held constant at freestream boundaries with inflow, and is only valid for an ideal gas. Specifying HOLD CHARACTERISTICS indicates that characteristic values are to be held constant. Note that the total pressure is always held fixed at freestream inflow boundaries, whether HOLD TOTALS is specified or not. The option specified will be applied at all the freestream boundaries in the specified zone(s).

The default is HOLD CHARACTERISTICS.

Note that the HOLD keyword only applies to freestream boundaries with subsonic inflow. See the HOLD_TOTALS keyword in the ARBITRARY INFLOW keyword block for information on holding total conditions at arbitrary inflow boundaries.

Note also that the syntax is slightly different for freestream and arbitrary inflow boundaries. For freestream boundaries, HOLD TOTALS and HOLD CHARACTERISTICS are used, without an underscore. For arbitrary inflow boundaries, HOLD_TOTALS and HOLD_CHARACTERISTICS are used in the ARBITRARY INFLOW keyword block, with an underscore.

See Also: TEST 103

IMPLICIT — Implicit operator control

Structured Grids

```
IMPLICIT {word1 [word2 word3 [zone_selector [tre]]] | \
          JACOBI jiter jcnv [RELAX jrel] [zone_selector] | \
          GAUSS giter gcnv [RELAX grel] [zone_selector] | \
          MACCORMACK [MAFK k] [zone_selector] | \
          OVERFLOW [zone_selector]}
```

Unstructured Grids

```
IMPLICIT {UGAUSS [JACOBIAN [PER] {FACE|CELL}] [BLOCK|DIAGONAL] \
          [SAVE_JACOBIAN] [SUBITERATIONS nsub] [zone_selector]}
```

This keyword allows user control of the implicit operator within each zone. There are five possible modes for structured grids, and one for unstructured grids.

Structured Grids

```
IMPLICIT word1 [word2 word3 [zone_selector [tre]]]
```

This form of the `IMPLICIT` keyword allows the user to turn off the implicit operator completely, resulting in an explicit calculation, or to use a scalar or full block implicit operator. With these options, a different implicit operator may be specified for each computational direction.

The user-specified parameters are defined as follows:

word1 A keyword controlling the ξ-direction implicit operator

word2 A keyword controlling the η-direction implicit operator

word3 A keyword controlling the ζ-direction implicit operator

tre Specifies the trapezoidal time differencing factor. The possible values are:

0	Explicit (but expensive, don't use)
1 or omitted	Implicit
0.5	Trapezoidal time differencing

The keywords that may be used for *word1*, *word2*, and *word3* are defined in the following table.

Keyword	Difference Scheme
`NONE`	Explicit
`SCALAR`	Scalar implicit operator (default for Euler solutions)
`FULL`	Full block implicit operator (default for viscous solutions)

Note that if only one of the above keywords is specified, Wind-US assumes that the specified operator is to be used in all directions in all zones.

`IMPLICIT JACOBI` *jiter* *jcnv* `[RELAX` *jrel*`]` `[`*zone_selector*`]`

This form of the `IMPLICIT` keyword turns on the point Jacobi implicit operator in the selected zone. The user-specified parameters are defined as follows:

jiter The number of subiterations allowed each time step. A typical value is 30.

jcnv The level of convergence to assume the subiterations are converged. A typical value is 0.0001.

jrel The relaxation factor. The default value is 1.0 (i.e., no relaxation).

`IMPLICIT GAUSS` *giter* *gcnv* `[RELAX` *grel*`]` `[`*zone_selector*`]`

This form of the `IMPLICIT` keyword turns on the Gauss-Seidel implicit operator in the selected zone. The user-specified parameters are defined as follows:

giter The number of subiterations allowed each time step. A typical value is 10.

gcnv The level of convergence to assume the subiterations are converged. A typical value is 0.0001.

grel The relaxation factor. The default value is 1.0 (i.e., no relaxation).

`IMPLICIT MACCORMACK [MAFK` *k*`]` `[`*zone_selector*`]`

This form of the `IMPLICIT` keyword turns on MacCormack's first-order modified approximate factorization (MAFk) procedure in the selected zone. The procedure attempts to remove the decomposition error by feeding the error term back into the matrix equations on the right-hand side.

The solution process requires subiterations, with the number of subiterations specified with the `MAFK` option by the parameter k. The default for k is 2.

For stability, the `IMPLICIT BOUNDARY` keyword should be used to specify that implicit boundary conditions are to be used with the MAFk procedure. In addition, when large CFL numbers are to be used, it is recommended that the CFL number be increased gradually (over 200 iterations or so) to the desired value using the `INCREMENT` parameter in the `CFL#` keyword.

The MAFk procedure has been demonstrated in Wind-US to be stable in two dimensions with very high CFL numbers (greater than 1000). In three dimensions, however, only limited testing has been done, and its efficiency has not yet been determined.

The MAFk procedure may not be used with second-order time marching.

`IMPLICIT OVERFLOW` `[`*zone_selector*`]`

This form of the `IMPLICIT` keyword specifies that the "ARC3D 3-factor diagonal scheme" as implemented in OVERFLOW 1.8q is to be used. Tests indicate that this scheme is faster than the other implicit schemes, and gives comparable answers.

This option is currently available only for 3-d perfect gas flows, with explicit boundary conditions. It also uses more memory than the other implicit schemes, due to the interface coding used to implement it in Wind-US.

See Also: `IMPLICIT BOUNDARY`, `IMPLICIT ORDER`

Unstructured Grids

```
UGAUSS [JACOBIAN [PER] {FACE|CELL}] [BLOCK|DIAGONAL] \
   [SAVE_JACOBIAN] [SUBITERATIONS nsub] [zone_selector]}
```

This form of the `IMPLICIT` keyword applies to unstructured grids, and specifies that a Gauss-Seidel implicit operator is to be used in the selected zone. The various options are as follows:

`JACOBIAN [PER] {FACE|CELL}` Specifies that the flux Jacobian is to be computed on each face (i.e., one per face), or each cell (i.e., two per face). If `CELL` is used, `SAVE_JACOBIAN` must also be used. The default is one per face.

`BLOCK|DIAGONAL` Specifies that the equations are to be solved as either a full block or diagonal matrix system. The default, if just `IMPLICIT UGAUSS` is specified, is a diagonal system. But, if the `IMPLICIT` keyword isn't used at all, the default is a full block matrix system.

`SAVE_JACOBIAN` If specified, the Jacobian(s) are saved between iterations. The default is to recompute them each iteration. It is recommended that `SAVE_JACOBIAN` be used when there is enough memory available. For a typical case, saving the Jacobian between iterations decreases the CPU time by about 15%, while increasing the memory requirements by 20%-40%.

`SUBITERATIONS` *nsub* Specifies the number of sub-iterations to be performed on each face, for each "iteration per cycle".

IMPLICIT BOUNDARY — Implicit boundary conditions

Structured Grids

```
IMPLICIT BOUNDARY {ON | OFF} [zone_selector]
```

This keyword controls the use of Wind-US's numerical boundary conditions within the implicit operator. The default mode is `OFF`, implying explicit boundary conditions. When `ON` is specified, implicit boundary conditions will be used at "wall"-type boundaries in structured grids.

Implicit boundary conditions cannot currently be used if the `IMPLICIT OVERFLOW` keyword is specified.

See Also: `IMPLICIT`

IMPLICIT ORDER — Order of implicit time marching

Structured Grids

```
IMPLICIT ORDER [ONE|TWO] [zone_selector]
```

This keyword sets the order of the implicit time marching scheme for structured grids. The default is first order. When `TWO` is specified, second-order time marching will be used.

Second-order time marching may be used with any structured grid implicit operator except MacCormack's modified approximate factorization procedure (`IMPLICIT MACCORMACK`). It may also be used in combination with Global Newton time marching.

See Also: `IMPLICIT`, `NEWTON`

INCLUDE — Include a file in the standard input

```
INCLUDE filename
```

This keyword allows the contents of an external file to be incorporated into Wind-US's standard input, just as if they were part of the input data (*.dat*) file. The *filename* must be either the full path name for the file, or a relative path name within the directory in which Wind-US is being run.

"Include" files may be nested.

INITIALIZE — Initialize in grid direction

Structured Grids

```
INITIALIZE [ALONG] [PLUS|MINUS] {I|J|K} [LINES] [zone_selector]
```

By default, in a new (i.e., non-restart) run, the direction for the initial velocity is determined by the information specified with the FREESTREAM and ARBITRARY INFLOW keywords. For structured grids, the INITIALIZE keyword may be used to specify that the initial velocity is in the $\pm i$, $\pm j$, or $\pm k$ direction. The magnitude of the initial velocity is unchanged.

Note that one of I, J, or K must be specified, and that the PLUS direction is the default.

See Also: FREESTREAM, ARBITRARY INFLOW

ITERATIONS — Set number of iterations per cycle

Structured Grids

```
{ITERATIONS [PER] [CYCLE] | ITER_CYCLE} n [PRINT [FREQUENCY] freq] \
   [zone_selector]
```

Unstructured Grids

```
{ITERATIONS [PER] [CYCLE] | ITER_CYCLE} n [zone_selector]
```

This keyword allows the user to control the number of iterations performed in each zone. The parameter n specifies the number of iterations per cycle (the default value is 5). In addition, n may have the following special values:

0 The indicated zone(s) will be bypassed, but the zone coupling will still take place. This is not a good idea as the active zone will update inactive ($n = 0$) zones, overwriting the existing data. This inactive zone will then pass the active zone's data back to it.

-1 Perform no iterations in the indicated zone and *do not* update this zone with adjacent zone information (but *do* pass this zone's frozen information to other zones each cycle).

-2 Perform no iterations in the indicated zone and *do not* update this zone with adjacent zone information (and *do not* pass this zone's frozen information to other zones).

For structured grids, residuals will be written to the *.lis* file every *freq* iterations, but only for cycles consistent with the `PRINT FREQUENCY` specified with the `CYCLES` keyword. The default value for *freq* is 1.

Note that the print frequency does not affect integrated properties specified using the `LOADS` keyword block. The print frequency for integrated properties is controlled by the `PRINT` keyword in the `LOADS` keyword block.

The *zone_selector*, if specified, must appear last. The print frequency, however, is global; the value specified on the last `ITERATIONS` entry in the input data (*.dat*) file will be used in all zones.

Example

For a structured grid, if the user specifies

```
CYCLES 1000 PRINT FREQUENCY 10
ITERATIONS PER CYCLE 10 PRINT FREQUENCY 5
```

cycle time information will be printed for cycles 1, 11, 21, etc. Residuals will be printed for iterations 10 (in cycle 1), 110 (cycle 11), 210 (cycle 21), etc.

See Also: `CYCLES`, `LOADS`, `NAVIER-STOKES ITERATIONS`, `TURBULENCE`

LOADS — Flowfield integration (block)

Structured Grids

```
LOADS
   [PRESSURE [OFFSET] {FREESTREAM | val}]
   PRINT [PLANES] [TOTALS] [ZONES] [LIFT | DRAG] [FREQUENCY freq] [MAKE_FRC file]
   [REFERENCE AREA aref]
   [REFERENCE LENGTH lref]
   [REFERENCE MOMENT [CENTER] xc yc zc]
   ZONE nzn
   SURFACE {I val | J val | K val} word1 [word2 [word3...]]
   SUBSET I range J range K range word1 [word2 [word3...]]
ENDLOADS
```

Unstructured Grids

```
LOADS
   [PRESSURE [OFFSET] {FREESTREAM | val}]
   PRINT [PLANES] [TOTALS] [ZONES] [LIFT | DRAG] [FREQUENCY freq] [MAKE_FRC file]
   [REFERENCE AREA aref]
   [REFERENCE LENGTH lref]
   [REFERENCE MOMENT [CENTER] xc yc zc]
   ZONE nzn
   SURFACE {I|U} val word1 [word2 [word3...]]
ENDLOADS
```

Flowfield properties may be integrated during the course of a Wind-US run to check convergence and solution quality. The values printed to the list file represent the force coefficients $F/A_r q_r$ and moment coefficients $M/L_r A_r q_r$ in the x, y, and z coordinate directions, where F and M are the force and moment, and L_r, A_r, and q_r are the reference values of length, area, and dynamic pressure. Integrated mass and momentum fluxes may also be computed. The values are written into the list output (*.lis*) file.

The various elements of the LOADS keyword block are defined below. Unless noted otherwise, the keywords apply to both structured and unstructured grids.

```
PRESSURE [OFFSET] {FREESTREAM | val}
```

This keyword controls the pressure integration. By default, the code uses $P - P_\infty$ in all pressure integrations, where P_∞ is the static pressure at freestream conditions. This keyword permits the user to specify the pressure offset value, such that:

FREESTREAM	Use $P - P_\infty$
val	Use $P - val$

```
PRINT [PLANES] [TOTALS] [ZONES] [LIFT | DRAG] [FREQUENCY freq] [MAKE_FRC file]
```

This keyword controls the output data from the integration. Options are turned 'on' by including the appropriate keyword.

`PLANES` Output the result of the integration for each surface and/or subset specified.

`TOTALS` Output integration grand totals over all the zones at the end of each cycle.

`ZONES` Output integration totals for each zone.

`LIFT | DRAG` Output lift, drag, and side forces instead of (x, y, z) force components. Directions for the lift, drag, and side force components are computed from the angles of attack and yaw specified using the `FREESTREAM` keyword.

`FREQUENCY` Output integration results (except for grand totals) every *freq* iterations.

`MAKE_FRC` Write grand totals to the summary file *file* at the end of each cycle, in addition to the *.lis* file. This requires that `PRINT TOTALS` also be specified.

```
REFERENCE AREA aref
REFERENCE LENGTH lref
REFERENCE MOMENT [CENTER] xc yc zc
```

These keywords specify the reference area *aref* in square inches; the reference length *lref* in inches; and the coordinates (*xc*,*yc*,*zc*) of the reference moment center in inches. The default values are 1.0 for *aref*, 1.0 for *lref*, and (0.0, 0.0, 0.0) for (*xc*, *yc*, *zc*).

```
ZONE nzn
```

This keyword specifies the zone number *nzn* for the surfaces and/or subsets which follow.

```
SURFACE {I val | J val | K val} word1 [word2 [word3...]]
```

This form of the `SURFACE` keyword applies to structured grids, and specifies the coordinate surface in zone *nzn* over which the integration is to be performed. The parameter *val* is a coordinate index specifying the surface.

The *word* parameters are keywords specifying what flowfield properties are to be computed, plus a couple of additional control values. The following keywords are currently available.

`FORCE` Compute pressure forces.

`MASS` Compute mass flow.

`MOMENT` Compute moments.

`MOMENTUM` Compute momentum.

`VISCOUS` Compute viscous force and moments.

`NORMAL` *inorm* *inorm* $= \pm 1$, specifying the desired normal vector direction; +1 for the increasing index direction and −1 for the decreasing index direction. *inorm* defaults toward the interior of the grid if the integration surface is on a boundary of the zone.

`NOSLIP`	Integrate only over points where the total velocity is 0.

At least one flowfield property must be specified. For integration surfaces that are not part of a zonal boundary, the normal direction must also be specified.

```
SURFACE {I|U} val word1 [word2 [word3...]]
```

This form of the `SURFACE` keyword applies to unstructured grids, and specifies the unstructured surface in zone *nzn* over which the integration is to be performed. The parameter *val* is the surface number.

The *word* parameters are keywords specifying what flowfield properties are to be computed. The following keywords are currently available.

`FORCE`	Compute pressure forces.
`MASS`	Compute mass flow.
`MOMENT`	Compute moments.
`MOMENTUM`	Compute momentum.
`VISCOUS`	Compute viscous force and moments.
`HEAT`	Compute heat flux. This keyword is only available for isothermal walls.

At least one flowfield property must be specified.

```
SUBSET I range J range K range word1 [word2 [word3...]]
```

This keyword may be used with structured grids to define a subset of a computational surface in zone *nzn* over which the integration is to be performed. The *range* parameters take one of the following forms:

index1 index2	Starting and ending indices in the specified direction. `LAST` may be used for the last index.
`ALL`	Equivalent to `1 LAST`.

For three-dimensional cases, the starting and ending indices for one (and only one) of the `I`, `J`, or `K` parameters must be the same. For two-dimensional cases, the `K` parameter must be specified as either `K 1 1` or `K ALL`; one or both of the `I` and `J` parameters may have different starting and ending indices.

The word parameters are the same as those described above for the `SURFACE` keyword for structured grids.

Example

```
LOADS
   PRESSURE OFFSET 0.0
   PRINT PLANES ZONES TOTALS LIFT FREQUENCY 2
   REFERENCE AREA 100.
```

```
      REFERENCE LENGTH 12.
      REFERENCE MOMENT CENTER 35. 36. 78.
      ZONE 4
         SUBSET I ALL J 1 1 K 15 LAST FORCE MOMENT VISCOUS NOSLIP
      ZONE 10
         SURFACE I 1 MOMENTUM MASS
   ENDLOADS
```

MARCHING — Parabolized Navier-Stokes algorithm

Structured Grids

```
MARCHING [LIMITER value] [CHECKPOINT interval] [COPY]
```

For structured grids, this keyword enables Wind-US's spatial marching, or parabolized Navier-Stokes (PNS), algorithm for flowfields which are supersonic in the computational i-direction. In this mode, Wind-US marches from the $i = 1$ to the $i = i_{max}$ computational surface, attempting to compute a steady-state solution at each plane before moving on to the next one. Using the PNS algorithm significantly reduces the computing time required for supersonic solutions.

`LIMITER` *value* — This keyword enables the marching limiter, which limits the change in the solution vector $\mathbf{Q}$ to $(value)\mathbf{Q}$. I.e.,

$$\Delta\mathbf{Q} \leq (value)\mathbf{Q}$$

`CHECKPOINT` *interval* — The parameter *interval* specifies the number of i-planes to be computed before writing the current flowfield to the solution file. The default is 10.

`COPY` — This keyword requests that Wind-US copy the solution from the most recently computed i-plane to the upcoming i-plane, giving a (hopefully) better initialization to the new i-plane than simply starting from freestream flow.

Notes

- Marching is only available for structured grids.
- Marching is only available when Wind-US is run in serial mode.
- Marching is not available with the one-equation turbulence models (`BARTH`, `SPALART`).
- Marching requires that one of the following explicit operators be used. (See the `RHS` keyword.)
  - Coakley (any order)
  - Roe (first-order upwind, second-order upwind, third-order upwind-biased, first-order upwind modified for stretched grids, or second-order upwind-biased modified for stretched grids)
  - Van Leer (first-order upwind, second-order upwind, or third-order upwind-biased)
- The Roe second-order upwind-biased explicit operator modified for stretched grids uses the $i + 1$ grid point, which is invalid in a PNS solution. When this operator is used, Wind-US automatically changes to first order in the i-direction.

See Also: `RHS`, `TURBULENCE`

MASS FLOW — Outflow boundaries, mass flow

Structured Grids

```
MASS [FLOW] {RATE [ACTUAL | CORRECTED] | RATIO} value \
   [PRESSURE | DIRECT [RELAXER rlxr]] [ORDER {ZERO|0|ONE|1}] \
   [ZONE] range1[,range2[, ...  rangen]]
```

Unstructured Grids

```
MASS [FLOW] {RATE [ACTUAL | CORRECTED] | RATIO} value \
   [ZONE] range1[,range2[, ...  rangen]]
```

This keyword allows the user to specify mass flow at outflow boundaries in the flowfield.

Structured Grids

The input keywords applicable to structured grids are as follows:

`RATE` *value* represents the mass flow rate in $\mathrm{lb_m}$/sec, and may be actual (the default) or corrected, as specified by the `ACTUAL` or `CORRECTED` keyword. The specified *value* must be positive. The corrected air flow is defined as

$$W_c = W_{actual} \frac{\theta_x^{0.5}}{\delta_x}$$

where

$$\delta_x = P_x / P_0 \qquad \theta_x = T_x / T_0$$

and P_x and T_x are the total pressure and temperature at the duct exit, and P_0 and T_0 are equal to 14.7 psi and 520 °R, respectively.

`RATIO` *value* represents the mass flow ratio. Again, the specified *value* must be positive. The actual mass flow is computed as

$$\dot{m} = (value) \rho_\infty U_\infty A_{cap}$$

where A_{cap} is the capture area found in the *.cgd* file zonal parameters.

`PRESSURE` A spatially-constant pressure is set at the boundary, and modified as the solution proceeds until the desired mass flow is achieved. This is the default.

`DIRECT` The momentum, and thus the mass flow, is modified directly, and the pressure adjusts as the solution proceeds.

`RELAXER` The specified mass-flow rate will be relaxed using the relaxtion factor *rlxr*. This option only applies when `DIRECT` is specified. The default value for *rlxr* is 1.0 (i.e., no relaxation).

`ORDER` Either zeroth- or first-order extrapolation will be used, as specified. The default is zeroth-order.

In the zone specification, the *range* parameter(s) must be one of the following forms:

zonenum	Selects zone *zonenum*
begzone : *endzone*	Selects all zones from *begzone* to *endzone*
`ALL`	Selects all zones

Note that if multiple zones are listed, the specified mass flow will be applied in *each* zone.

With the `PRESSURE` option, the pressure will be constant over the entire outflow boundary, resulting in poor solutions for flows that should have cross-flow pressure gradients in that region. With the `DIRECT` option, cross-flow pressure gradients may be present at the outflow boundary, and the mass flow will be equal to the user-specified value (for *rlxr* = 1) for all iterations.

For flows with negligible cross-flow pressure gradients, the results and convergence rates using the `PRESSURE` and `DIRECT` options are nearly the same. For a test case with a significant cross-flow pressure gradient near the outflow boundary, the computed pressures using the two options differed by as much as 10%. The `PRESSURE` option, although non-physical for this case, had a slightly better convergence rate.

Internally, to apply this boundary condition Wind-US does the following:

1. At all the boundary points, the density, momentum, and energy are extrapolated from the interior to the boundary using either zeroth- or first-order extrapolation, as specified.
2. The mass flow at the boundary is computed by numerical integration.
3. If `PRESSURE` was specified, a new downstream pressure is computed based on the difference between the computed and specified mass flow rates.
4. If `DIRECT` was specified, a mass flow correction factor is computed as

   $$f_{corr} = 1 + r\left(\frac{\dot{m}_{spec}}{\dot{m}_{int}} - 1\right)$$

   where r is the input relaxation factor *rlxr*, and $\dot{m}_{spec}$ and $\dot{m}_{int}$ are the user-specified and integrated mass flow rates, respectively.
5. For each boundary point, the density and momentum, plus the pressure, effective gamma, compressibility factor, and speed of sound, are extrapolated from the interior to the boundary using either zeroth- or first-order extrapolation, as specified.
6. If `DIRECT` was specified, the extrapolated momentum values at the outflow boundary are modified using

   $$\begin{aligned}(\rho u) &= f_{corr}(\rho u)_{ext}\\(\rho v) &= f_{corr}(\rho v)_{ext}\\(\rho w) &= f_{corr}(\rho w)_{ext}\end{aligned}$$

7. If `PRESSURE` was specified, the energy at each boundary point is computed, consistent with the downstream pressure value from step 3 and the extrapolated values of density, etc., from step 5.
8. If `DIRECT` was specified, the energy at each boundary point is computed, consistent with the momentum values from step 6 and the extrapolated values of density, pressure, etc., from step 5.

Extrapolation Notes

The default for all extrapolation is zeroth-order (i.e., conditions at the boundary are set to the values at the computational plane adjacent to the boundary). This results in a discontinuous slope in flow values near the outflow boundary, which may be important for flows with significant streamwise pressure gradients. First-order extrapolation yields smoother results.

For flows with little or no streamwise pressure gradient near the outflow boundary, the results using zeroth- and first-order extrapolation are essentially identical. Convergence rates and the final residual values are generally better with zeroth-order extrapolation, however, so the default zeroth-order extrapolation is recommended.

For flows with significant streamwise pressure gradients near outflow boundaries, zeroth-order extrapolation can give poor results at the outflow boundary, and in some cases these can affect values at the inflow boundary. First-order extrapolation is thus recommended for these flows.

Examples

```
    MASS FLOW RATIO           0.95 ZONE 2
    MASS FLOW RATE  ACTUAL    180. ZONE 3
    MASS FLOW RATE  CORRECTED 220. ZONE 4
```

See Also: `COMPRESSOR FACE`, `DOWNSTREAM PRESSURE`, `DOWNSTREAM MACH`

Unstructured Grids

The input keywords applicable to unstructured grids are as follows:

`RATE` *value* represents the mass flow rate in lb_m/sec, and may be actual (the default) or corrected, as specified by the `ACTUAL` or `CORRECTED` keyword. The specified *value* must be positive. The corrected air flow is defined as

$$W_c = W_{actual}\frac{\theta_x^{0.5}}{\delta_x}$$

where

$$\delta_x = P_x/P_0 \qquad \theta_x = T_x/T_0$$

and P_x and T_x are the total pressure and temperature at the duct exit, and P_0 and T_0 are equal to 14.7 psi and 520 °R, respectively.

`RATIO` *value* represents the mass flow ratio. Again, the specified *value* must be positive. The actual mass flow is computed as

$$\dot{m} = (value)\rho_\infty U_\infty A_{cap}$$

where A_{cap} is the capture area found in the *.cgd* file zonal parameters.

In the zone specification, the *range* parameter(s) must be one of the following forms:

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
`ALL`	Selects all zones

Note that if multiple zones are listed, the specified mass flow will be applied in *each* zone.

For unstructured grids, a spatially-constant pressure is set at the boundary, and modified as the solution proceeds until the desired mass flow is achieved. No DIRECT option is available. The application of the pressure is under-relaxed, but DEBUG option 37 may be used to apply the pressure immediately, without under-relaxation. In addition, the extrapolation for unstructured grids is zeroth-order.

See Also: DOWNSTREAM PRESSURE, DEBUG 37

MFD — Magneto-Fluid Dynamics Model (block)

Structured Grids

```
MFD
   [OUTPUT {BFIELD | CONDUCTIVITY | CURRENT | EFIELD | VOLTAGE | LORENTZ}]
   [RELAX_MFD nriter]
   [UPDATE nuiter]
   [RADIATION emiss lref [tback]]
   {LORENTZ FILE FREQUENCY f [DUTY du] [SCALE sc] \
            PHASES n PATTERNS p1 p2 p3 ... pn
    |
    {CONDUCTIVITY | SIGMA} {CONSTANT sigma | \
                            CFL | \
                            EQUILIBRIUM {ARGON | AIR | GAS} [POTASSIUM mk] | \
                            LINEAR t1 sig1 t2 sig2 | \
                            PREDICTED [USING] [LIN-RESSLER | BOEING]}
    BFIELD {CONSTANT bz | BLOCKS nbblocks | CFL}
    {EFIELD {CONSTANT ey | BLOCKS neblocks | CFL} | \
     VOLTAGE {BOUNDARIES nvbnd | CFL | PARAMETERS mitvlt vlttol vltrx vltry vltrz vltfac}
    }
   }
ENDMFD
```

The `MFD` keyword block allows the user to specify the magneto-fluid dynamics mode and input data for the desired forms of the magnetic and electric fields, the electrical conductivity, output variables, and approximate radiation energy losses. This capability is only available for structured grids.

Control Functions

```
MFD
```

Defines the beginning of the MFD block.

```
ENDMFD
```

Defines the end of the MFD block.

```
OUTPUT {BFIELD | CONDUCTIVITY | CURRENT | EFIELD | VOLTAGE | LORENTZ}
```

The specified data will be written into into the flow (*.cfl*) file. Multiple `OUTPUT` keywords may be specified, to write multiple types of data into the *.cfl* file.

```
RELAX_MFD nriter
```

The MFD source terms will be relaxed over *nriter* iterations. The default for *nriter* is 1.

```
UPDATE nuiter
```

The MFD source terms will be updated every *nuiter* Navier-Stokes iterations. The default for *nuiter* is 1.

```
RADIATION emiss lref [tback]
```

Estimate the energy loss due to thermal radiation of the fluid with emissivity *emiss*, optical depth *lref*, and background temperature *tback* (°R). The default for *tback* is the freestream static temperature.

Body Force Determination

The body force resulting from the MFD terms can be added in one of two ways: (1) by directly specifying the Lorentz force; or (2) by specifying the conductivity, the magnetic field, and either the electric field or voltage.

The following keyword is used to directly specify the Lorentz force. If this method is used, the `CONDUCTIVITY`, `BFIELD`, `EFIELD`, and `VOLTAGE` keywords are not allowed.

```
LORENTZ FILE FREQUENCY f [DUTY du] [SCALE sc] \
        PHASES n PATTERNS p1 p2 p3 ... pn
```

nl Lorentz force distributions are stored in a *.cem* file named *FOR015.* This distribution is spread over space depending upon the phasing patterns. The pattern changes *n* times during a cycle.

`FREQUENCY` *f*	Number of cycles/second
`DUTY` *du*	Force is on the first *du* portion of a phase. The default value is 1.0.
`SCALE` *sc*	Multiply the Lorentz force by *sc* before adding it to the equations. The default value is 1.0.
`PHASES` *n*	Number of pattern phases in a cycle
`PATTERNS` *p1 p2 p3 ... pn*	The Lorentz force distribution to use in each phase. Must correspond to the *nl* distributions stored in the *.cem* file.

If the Lorentz force is not directly specifed using the `LORENTZ` keyword, you must use the `CONDUCTIVITY` and `BFIELD` keywords to specify the conductivity and the magnetic field, and either the `EFIELD` or `VOLTAGE` keywords to specify the electric field or voltage.

```
{CONDUCTIVITY | SIGMA} {CONSTANT sigma | \
                        CFL | \
                        EQUILIBRIUM {ARGON | AIR | GAS} [POTASSIUM mk] | \
                        LINEAR t1 sig1 t2 sig2 | \
                        PREDICTED [USING] [LIN-RESSLER | BOEING]}
```

This keyword specifies the electrical conductivity in mhos/meter.

`CONSTANT` *sigma*	Hold the conductivity constant at the value *sigma*
`CFL`	Read the conductivity from the flow (*.cfl*) file

`EQUILIBRIUM {ARGON | AIR | GAS} [POTASSIUM` *mk*`]`
Estimate the electron density as a function of temperature for the indicated gas as input to the Lin & Ressler conductivity model. The default gas is air. If `POTASSIUM` *mk* is specified, the effect of the mass fraction *mk* of potassium will be included.

`LINEAR` *t1 sig1 t2 sig2* Set the conductivity to *sig1* at and below the temperature *t1*; to *sig2* at and above the temperature *t2*; and use a linear distribution for temperatures between *t1* and *t2*. The temperatures are in °R.

`PREDICTED [USING] [LIN-RESSLER | BOEING]`
Use real-gas predicted electron densities for input to the indicated conductivity model. The default is the Lin & Ressler model.

`BFIELD {CONSTANT` *bz* `| BLOCKS` *nbblocks* `| CFL}`

This keyword specifies the magnetic field in tesla.

`CONSTANT` *bz* Hold the magnetic field constant at the value *bz*, in the *z* coordinate direction

`BLOCKS` *nbblocks* Specify the magnetic field by reading in *nbblocks* blocks of data containing the magnetic field vector at selected coordinate points. The data immediately follows the `BFIELD BLOCKS` keyword. See the **Field Block Description** for details and an example.

`CFL` Read the magnetic field from the flow (*.cfl*) file

`EFIELD {CONSTANT` *ey* `| BLOCKS` *neblocks* `| CFL}`

This keyword specifies the electric field in Volts/meter.

`CONSTANT` *ey* Hold the electric field constant at the value *ey*, in the *y* coordinate direction

`BLOCKS` *neblocks* Specify the electric field by reading in *neblocks* blocks of data containing the electric field vector at selected coordinate points. The data immediately follows the `EFIELD BLOCKS` keyword. See the **Field Block Description** for details and an example.

`CFL` Read the electric field from the flow (*.cfl*) file

`VOLTAGE {BOUNDARIES` *nvbnd* `| CFL | PARAMETERS` *mitvlt vlttol vltrx vltry vltrz vltfac*`}`

With this keyword the electric field is determined by specifying the electric potential.

`BOUNDARIES` *nvbnd* Specify the electric potential at *nvbnd* zonal boundary regions. The data immediately follows the `VOLTAGE BOUNDARIES` keyword. See the **Voltage Boundary Description** for details and an example.

`CFL` Read the electric potential field from the flow (*.cfl*) file

`PARAMETERS` *mitvlt vlttol vltrx vltry vltrz vltfac*

Iterate a maximum of *mitvlt* iterations (the default is 10,000) to a tolerance of *vlttol* (a positive value means to a level of *vlttol*, a negative value means $|vlttol|$ orders of magnitude; the default is a level of 10^{-12}) with implicit factors *vltrx*, *vltry*, and *vltrz* (currently these must all be set to 0.0) and with an over-relaxation factor of *vltfac* (a typical value is 0.4).

Field Block Description

By using the `BFIELD BLOCKS` and/or `EFIELD BLOCKS` keywords, the magnetic and/or electric field may be determined from blocks containing the field vector at selected coordinate points. Each block consists of eight points in space, with the corresponding field vector at each of those points. The region contained within the blocks is filled using tri-linear interpolation between the specified points. Up to eight blocks may be specified for each field type. The spatial locations of the blocks may overlap, with the later-specified blocks overwriting the earlier ones.

There are eight lines of input per block, one for each of the eight coordinate points. Each line contains six values—the x, y, and z coordinates, and the field vector components in the x, y, and z directions.

The following example specifies the magnetic field using two blocks. (The comments in a slanted font are not part of the input.)

```
BFIELD BLOCKS 2
     60.0    0.0   0.0    0.0   0.0   0.0    Upstream plane of block 1
     60.0   20.0   0.0    0.0   0.0   0.0
     60.0    0.0   1.0    0.0   0.0   0.0
     60.0   20.0   1.0    0.0   0.0   0.0
    120.0    0.0   0.0    0.0   0.0  10.0    Downstream plane of block 1
    120.0   20.0   0.0    0.0   0.0   5.0
    120.0    0.0   1.0    0.0   0.0  10.0
    120.0   20.0   1.0    0.0   0.0   5.0
    120.0    0.0   0.0    0.0   0.0  10.0    Upstream plane of block 2
    120.0   20.0   0.0    0.0   0.0   5.0      (same as downstream of 1)
    120.0    0.0   1.0    0.0   0.0  10.0
    120.0   20.0   1.0    0.0   0.0   5.0
    180.0    0.0   0.0    0.0   0.0   0.0    Downstream plane of block 2
    180.0   20.0   0.0    0.0   0.0   0.0
    180.0    0.0   1.0    0.0   0.0   0.0
    180.0   20.0   1.0    0.0   0.0   0.0

        x      y     z     Bx    By    Bz
```

Voltage Boundary Description

Voltage boundaries are used to specify the boundary conditions at zone boundaries for the electric potential solver. The electric potential solver will take into account gradients and discontinuities in conductivity, as well as the electromotive force (EMF) induced by the fluid motion through the magnetic field. Currently, accurate voltage predictions require a grid with low skewness.

Up to 64 boundaries may be specified. The conditions at each boundary are specified on a single line, with eight values—*zone*, *face*, *type*, *L1*, *L2*, *M1*, *M2*, *value*—defined as follows:

zone Zone containing the boundary

face The boundary face, specified as a number from 1 to 6 corresponding to the i_1, i_{max}, j_1, j_{max}, k_1, and k_{max} face, respectively

type The boundary type, specified as 0 for a reflection boundary, and 1 for specified voltage

L1, L2, M1, M2 The indices on the face over which the boundary condition applies, as follows

Face	Indices
i_1 or i_{max}	j_{low}, j_{high}, k_{low}, k_{high}
j_1 or j_{max}	k_{low}, k_{high}, i_{low}, i_{high}
k_1 or k_{max}	i_{low}, i_{high}, j_{low}, j_{high}

value The voltage for specified-voltage boundaries; 0.0 for reflection boundaries

The following example specifies eight voltage boundaries. (The comments in a slanted font are not part of the input.)

```
VOLTAGE BOUNDARIES 8
   1     1     0     1    30     1     1       0.0
   1     1     1    31    61     1     1       0.0
   1     2     1     1    31     1     1   10000.0
   1     2     0    32    61     1     1       0.0
   1     3     0     1     1     1    30       0.0
   1     3     1     1     1    31    61   10000.0
   1     4     1     1     1     1    31       0.0
   1     4     0     1     1    32    61       0.0

 Zone  Face  Type   L1    L2    M1    M2      Value
```

MOVING WALL — Specify moving wall boundaries

Structured Grids

```
MOVING [WALL] iblreg {[TRANSLATE {I | X} speed] | [SPIN X rps yc zc]}
```

For structured grids, this keyword allows no-slip walls to have a tangential velocity.

iblreg Moving walls are activated in regions specified as bleed in the *.cgd* file (set with GMAN). *iblreg* is the bleed region number.

`TRANSLATE I` Move wall in the *i*-direction at the velocity *speed*, in feet per second.

`TRANSLATE X` Move wall in the *x*-direction at the velocity *speed*, in feet per second.

`SPIN X` Move wall to model rotation about the *x*-axis (wall should be spinning and tangent to this motion).

rps Rotation speed in radians per second

yc,zc Coordinates of the center of rotation in the *y*-*z* plane

NAVIER-STOKES ITERATIONS — Navier-Stokes sub-iterations

Structured Grids

```
NAVIER-STOKES ITERATIONS iter [zone_selector]
```

For structured grids, Wind-US organizes the equations to be solved into logical "groups" that are solved together. It also allows multiple iterations of a specific group (i.e., sub-iterations) for each "iteration per cycle". (The number of iterations per cycle is set using the `ITERATIONS` keyword.)

The `NAVIER-STOKES ITERATIONS` keyword allows the user to specify the number of sub-iterations for the Navier-Stokes equation group (which includes any chemical species equations) performed in each zone for each "iteration per cycle". The default value is one, indicating that each "iteration per cycle" corresponds to one iteration of the Navier-Stokes equations. Note that if *iter* is set to zero, the Navier-Stokes equations will not be solved at all.

See Also: `ITERATIONS`, `TURBULENCE`

NEWTON — Use Global Newton time stepping

Structured Grids

```
NEWTON [TIME LEVELS newstp] [CONVERGE {LEVEL | ORDER} newcvg]
```

For structured grids, this keyword may be used to specify that the Global Newton time stepping algorithm is to be used. The parameter *newstp* specifies the number of Global Newton time levels to advance. The default value is 30.

There are two possible procedures for determining the overall global convergence.

`CONVERGE LEVEL` Convergence is assumed when

$$|\mathbf{Q}^n - \mathbf{Q}^{n-1}| < \mathit{newcvg}$$

where $\mathbf{Q}$ represents the vector of dependent variables, and n is the Newton time level.

`CONVERGE ORDER` Convergence is assumed when

$$\frac{|\mathbf{Q}^n - \mathbf{Q}^{n-1}|}{\max(|\mathbf{Q}^n - \mathbf{Q}^{n-1}|)} < 10^{-\mathit{newcvg}}$$

The default is `CONVERGE ORDER 3`.

Within a Newton time level, the number of cycles and iterations to be run is specified using the `CYCLES` and `ITERATIONS` keywords.

The convergence criteria within a Newton time level may be specified using the `CONVERGE` keyword. Note that the default for the `CONVERGE` keyword is a four-order of magnitude decrease in the maximum residual. If Newton iteration is being used for a steady flow problem, with the default of three orders of magnitude for the global convergence criteria, it would make sense to also use three orders of magnitude for the convergence criteria within a Newton time step.

See Also: `CYCLES`, `ITERATIONS`, `CONVERGE`, `IMPLICIT ORDER`

OUTFLOW NON-REFLECTING — Outflow boundaries, non-reflecting

Structured Grids

```
OUTFLOW [NON-REFLECTING] [ZONE] range1[,range2[, ... rangen]]
```

This keyword imposes a non-reflecting, subsonic outflow boundary condition at outflow boundaries in structured zones. Acoustic disturbances reaching the boundary are essentially eliminated. It is actually implemented using the Paynter compressor face model (Slater and Paynter, 2000), but with the response coefficients α and β set to zero.

In the zone specification, the *range* parameter(s) must be one of the following forms:

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
`ALL`	Selects all zones

This boundary condition is intended to be used for time-accurate flows with a CFL number less than one; however, it may be applicable in certain cases for steady-state simulations.

See Also: `COMPRESSOR FACE PAYNTER`

PERIODIC — Periodic boundaries

Periodic boundaries are currently supported only for structured grids. They are treated as normal coupled boundaries, with the connection data stored in the grid (*.cgd*) file. No keyword is needed in the input data (*.dat*) file.

GMAN's `CONNECT MODE` option is used to specify how to move one boundary surface to overlay it on the corresponding periodic boundary surface. There are two connection modes — translation and rotation. For translation, the user defines the Δx, Δy, and Δz movement for the surface. For rotation the user sets the center of rotation and the angles. The periodic boundary surfaces do not have to be in the same zone, nor do they have to be point matched. They only have to line up physically once the movement has been performed.

Details about how to set a periodic boundary condition in GMAN are presented in Section 5.6.1 starting on page 52.

PRANDTL — Set the laminar and turbulent Prandtl numbers

```
PRANDTL Prl Prt
```

This keyword may be used to set the laminar and turbulent Prandtl numbers. The default values are 0.72 and 0.9, respectively.

Note that the Prandtl numbers may also be set using the GAS keyword.

See Also: GAS

PRECOND — Pre-conditioning for low Mach number flows

Unstructured Grids

```
PRECOND eps_pre
```

This keyword may be used to apply matrix pre-conditioning to improve (or allow) convergence for flows at low Mach numbers. While it theoretically may be used at all Mach numbers, it increases the CPU time required for each time step, and is therefore recommended for use only when the Mach number is less than about 0.05.

The input parameter eps_{pre} is an artificial compressibility factor. The recommended value is

$$eps_{pre} = \max(\sqrt{3}M_\infty, 0.2)$$

where M_∞ is the freestream Mach number. Very small values for eps_{pre} will lead to very large values for artificial compressibility, and convergence problems, especially when stagnation regions are present. Values of eps_{pre} that are too large will decrease the amount of pre-conditioning, leading to slow (or no) convergence.

Additional details on the implementation of the pre-conditioning scheme, and results for various test cases, are presented by Liu and Ramakrishnan (2004).

Q LIMIT — Limit pressure and density

Unstructured Grids

```
Q [LIMIT] [PRESSUREMIN pmin] [PRESSUREMAX pmax] \
          [DENSITYMIN  dmin] [DENSITYMAX  dmax]
```

This keyword may be used, with unstructured grids only, to set limits on the pressure and density to aid convergence. The limits *pmin*, *pmax*, *dmin*, and *dmax* are non-dimensional, normalized by the freestream static values. The default values are $pmin = dmin = 0.01$ and $pmax = dmax = 250$. In practice, setting the maximums to about two or three times the stagnation values is reasonable.

Note while the limits can be set to very small (or large) values, the limiting cannot be turned off. Specifying a limit as zero or a negative value results in the default being used.

See Also: `DQ LIMITER`

REINITIALIZE — Reinitialize selected flowfield zones on restart

Structured Grids

```
REINITIALIZE {MODE {AUTO | NOAUTO} | \
              [ZONE] range1[,range2[, ...  rangen]] [IJK_RANGE]}
```

Unstructured Grids

```
REINITIALIZE {MODE {AUTO | NOAUTO} | \
              [ZONE] range1[,range2[, ...  rangen]]}
```

This keyword may be used to reinitialize the flow conditions in specified zones after a restart. The reinitialization will be done as if Wind-US were being run from scratch, i.e., to freestream values, or (for structured zones) to values specified using the `ARBITRARY INFLOW` and/or `BL_INIT` keywords, as described in Section 3.6 starting on p. 36.

In the zone specification, the *range* parameter(s) must be one of the following forms:

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
`ALL`	Selects all zones

For structured zones, `REINITIALIZE` may be used in conjunction with the `ARBITRARY INFLOW` keyword to reinitialize only selected portions of the flow. If the `IJK_RANGE` parameter is specified with the `REINITIALIZE` keyword, conditions will be reinitialized only at those points specified via the `IJK_RANGE` parameter on the `ARBITRARY INFLOW` keyword. If the `IJK_RANGE` parameter is not specified with the `REINITIALIZE` keyword, the conditions at all the grid points in the specified zones will be reinitialized.

Multiple `REINITIALIZE` keywords are permitted, each on a separate line in the input data file.

Normally, a restart run will abort if the grid size for a zone in the grid (*.cgd*) file is different from its size in the flow (*.cfl*) file (unless `ITERATIONS PER CYCLE` is set to −2 for the zone in question, indicating that it plays no part in the calculation). However, if the `REINITIALIZE` keyword is used to specify that the zone is being reinitialized, Wind-US will automatically reset the grid size in the *.cfl* file to match the size in the *.cgd* file.

Further, if `REINITIALIZE MODE AUTO` is specified, and if the grid size for a zone is different in the *.cgd* and *.cfl* files, Wind-US will automatically reset the zone size in the *.cfl* file to match the size in the *.cgd* file, and reinitialize the zone, even if it's not explicitly listed using a `REINITIALIZE` keyword.

Examples

The following example will reinitialize flow conditions in zones 1 and 3. If the grid sizes for those zones aren't the same in the existing *.cgd* and *.cfl* files, the grid size in the *.cfl* file will be reset to match the size in the *.cgd* file. If the grid size for any other zone is different in the *.cgd* and *.cfl* files, the run will abort.

```
REINITIALIZE ZONE 1
REINITIALIZE ZONE 3
```

The following example will also reinitialize flow conditions in zones 1 and 3, again resetting the grid size in the *.cfl* file to match the size in the *.cgd* file, if necessary. But in this example, if the grid size for any other zone is different in the *.cgd* and *.cfl* files, that zone will also be reinitialized, and the grid size in the *.cfl* file will be reset to match the size in the *.cgd* file.

```
REINITIALIZE MODE AUTO
REINITIALIZE ZONE 1
REINITIALIZE ZONE 3
```

See Also: ARBITRARY INFLOW, BL_INIT, FREESTREAM

RELAX COUPLING — Set zone coupling relaxation factor

Structured Grids

```
RELAX {COUPLE | COUPLING} factor \
   [ZONE range1[,range2[, ...  rangen]] \
    [[BOUNDARY] {ALL | I1 | IMAX | J1 | JMAX | K1 | KMAX}]]
```

This keyword allows the user to specify the relaxation factor when using characteristic zone coupling and structured grids. *factor* may range from 0.0 for no coupling, to 1.0 for full zone coupling. In the zone specification, the *range* parameter(s) must be one of the following forms:

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
begzone:	Selects all zones from *begzone* to `MAXZONE`, the total number of zones in the grid file
:*endzone*	Selects all zones from 1 to *endzone*
`ALL`	Selects all zones

If the zone specification is omitted, the specified *factor* will be applied at all boundaries in all zones. Note that a boundary cannot be specified without the zone specification.

If a zone (or zones) is specified, but the boundary is not (or the boundary is specified as `BOUNDARY ALL`), the specified *factor* will be applied at all boundaries in the specified zone(s).

The default relaxation factor is 0.7 for steady-state calculations, and 1.0 for for space-marching and time-accurate calculations. If the `RELAX COUPLING` keyword is used, and all zones are selected (either by omitting the zone specification, or by specifying `ZONE ALL`), the relaxation factor is automatically set to 1.0 for space-marching and time-accurate calculations. However, if specific zones were selected, the specified *factor* will be used at the specified boundary in those zones, even for space-marching and time-accurate calculations.

REL-ROT-ZONE — Relative rotating zones (block)

Structured Grids

```
REL-ROT-ZONE
   ZONE iz1 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
        [SUBSET I range J range K range]
   ZONE iz2 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
        [SUBSET I range J range K range]
   ROTATING-ZONE flag
ENDRRZ
```

[Note - The capability to use the `ROTATE` *keyword to specify rotating reference frames on a zonal basis has temporarily been removed. Until it is restored, the* `REL-ROT-ZONE` *keyword block will not work as advertised.]*

For structured grids, the `REL-ROT-ZONE` keyword block, along with the `ROTATE` keyword, may be used to specify that one zone is rotating relative to another zone. This "relative rotating zone" capability is intended to simulate rotating devices such as compressor fans. The `ROTATE` keyword is used to specify which zone(s) are rotating, plus the rotation axis and rate. The `REL-ROT-ZONE` keyword block specifies the location of the interface between the two zones, and how flow conditions are to be transferred between zones.

Zones sharing an interface may have different circumferential extents. Thus, when modeling a turbomachinery component like a compressor, only one blade per stage is required. Multiple zones and zonal interfaces may be used to cover the radial extent of the stage-to-stage interface, but a single zone must be used in the circumferential direction. The interface surface must correspond to a surface of revolution and grid lines in the circumferential direction must be at a constant radius relative to the rotation axis. The rotation axis must correspond to a coordinate axis.

As noted above, this capability is intended to simulate rotating devices such as compressor fans. A typical configuration would be an upstream non-rotating zone covering the full 360° cross-section, and a rotating downstream zone (or zones, if multiple zones are used in the radial direction) with a circumferential extent of $360°/N$ corresponding to a single blade. Periodic boundary conditions would be set at the circumferential boundaries in the rotating zone(s), using GMAN's rotational coupling mode, as described in Section 5.6.1.

The coupling of the downstream face of the non-rotating zone to the upstream face of the rotating zone would also be done using GMAN's rotational coupling mode, repeated $N - 1$ times. This will couple all the points except for that portion of the face that corresponds to the downstream zone in its non-rotated position. These remaining points are then coupled using ordinary (i.e., non-rotated) coupling mode.[31]

The elements of the `REL-ROT-ZONE` keyword block are defined as follows:

```
REL-ROT-ZONE
```

Defines the beginning of the relative rotating zone block.

[31] In Wind-US, non-zero rotation angles trigger the use of a rotationally periodic boundary condition. Since this is *not* what we want between two relative rotating zones, this "non-rotated" coupling should be done *last*, so that zero rotation angles are written into the common grid (*.cgd*) file.

```
ZONE iz1 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
     [SUBSET I range J range K range]
ZONE iz2 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
     [SUBSET I range J range K range]
```

These two lines define the interface between the two zones. The relevant zones are given by the values of *iz1* and *iz2*, and the relevant boundaries within zones *iz1* and *iz2* are specified via the `BOUNDARY` keyword parameter.

iz1 Zone to which increments will be added when passing information to *iz2*

iz2 Zone receiving positive increments, increments will be subtracted when passing information back to zone *iz1*

The `SUBSET` parameter may be used to specify that the change in properties occurs only over a part of the zone boundary. Otherwise, it is assumed that the change occurs over the entire boundary. The *range* parameters define the part of the zone boundary over which the change occurs, and take one of the following forms:

index1 index2 Starting and ending indices in the specified direction. `LAST` may be used for the last index.

`ALL` Equivalent to `1 LAST`.

The starting and ending indices for the appropriate `I`, `J`, or `K` parameter (depending on the boundary specified) must be the same, and correspond to that boundary.

```
ROTATING-ZONE flag
```

flag defines how data is to be communicated between the two zones. Currently the only valid values are:

0 if the zones are not rotating relative to each other. This is the default.

2 for circumferential averaging. This permits the communication of the bulk fluid properties between zones, while maintaining radial distributions and the efficiency of local time stepping.

```
ENDRRZ
```

Defines the end of the relative rotating zone block.

Example

Figure 8 shows a four-zone configuration. Zone 1 is non-rotating, and zones 2, 3, and 4 are rotating about the x axis at 1680 radians/sec in the counter-clockwise direction. The figure shows the grid from the side in a constant-θ plane, and at the interface plane between the non-rotating and rotating zones, looking downstream.

The non-rotating zone 1 covers the full 360° cross section, but the rotating zones 2–4 cover just 36°. As noted previously, zones sharing an interface may have different circumferential extents.

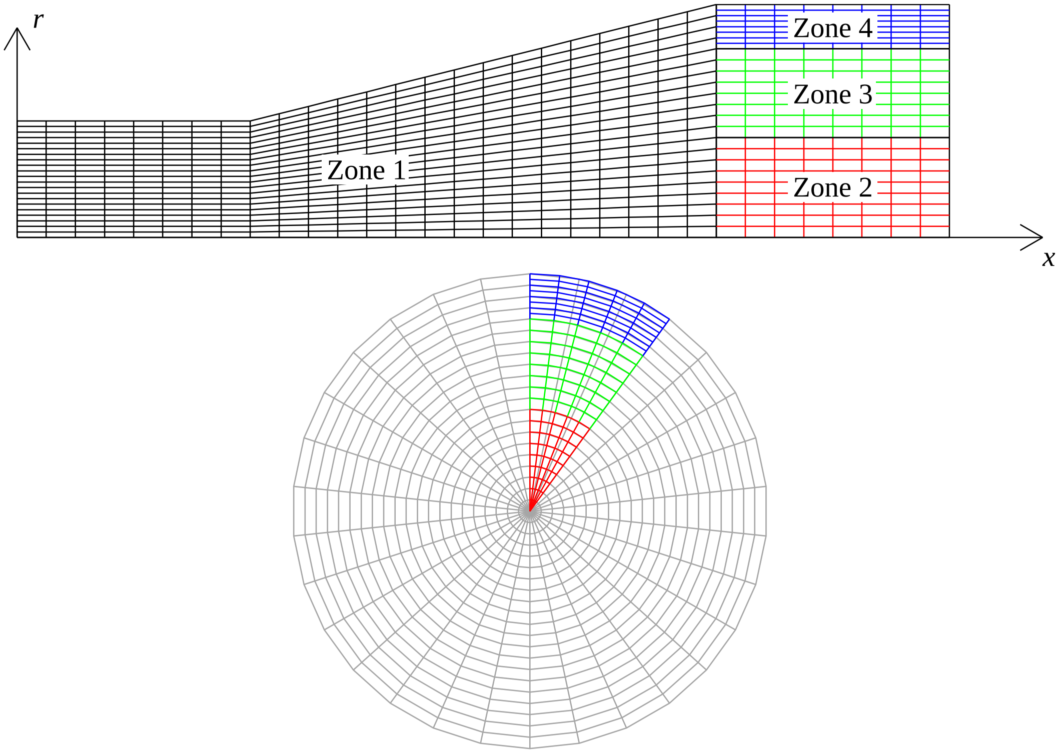


Figure 8: Example grid with relative rotating zones

This particular configuration is similar to one that might be used to model a single blade from a compressor blade row with 10 blades.

The indices i, j, and k are in the axial, radial, and circumferential directions, respectively.

For this configuration, the zone coupling was done in GMAN as described below. In this discussion, the "boundary zone" is the one containing grid points for which a boundary condition is being set. GMAN is used to set the connectivity between points in the boundary zone to points in the "source zone". The source zone is specified using GMAN's "`SEL OTHER BND`" menu choice.

1. Run "auto-couple", which results in the following coupling:

Zone	Boundary		Zone	Boundary
1	`IMAX`	$\Longleftarrow$	2	`I1`
1	`IMAX`	$\Longleftarrow$	3	`I1`
1	`IMAX`	$\Longleftarrow$	4	`I1`
2	`JMAX`	$\Longleftrightarrow$	3	`J1`
3	`JMAX`	$\Longleftrightarrow$	4	`J1`

   Note that "auto-couple" couples the upstream faces of zones 2–4 to the downstream face of zone 1, but not vice-versa.

2. Manually couple the zone 1 `K1` surface ($\theta = 0°$) to the zone 1 `KMAX` surface ($\theta = 360°$), and vice versa, using ordinary coupling.

3. Couple the `K1` and `KMAX` surfaces in zone 2 as periodic boundaries, as described in Section 5.6.1.

   (a) Use zone 2, boundary `K1`, as the "boundary zone", and zone 2, boundary `KMAX`, as the "source zone".

   (b) Use `1` (rotation) as the connection mode, a point on the x axis as the center of rotation, and `36.0 0.0 0.0` for the rotation angles (in degrees, without commas, and positive for the `+K` direction).

   (c) Repeat the above two steps, but using zone 2, boundary `K1`, as the "boundary zone", zone 2, boundary `KMAX`, as the "source zone", and `-36.0 0.0 0.0` for the rotation angles.

   (d) Repeat the above three steps for zones 3 and 4.

4. Couple the zone 1 `IMAX` surface to the zone 2 `I1` surface, using rotational coupling mode repeatedly. The procedure is very similar to specifying periodic coupling.

   (a) For the first rotation:

   - In graphics mode, from GMAN's main menu select `BOUNDARY COND`.
   - Pick zone 1, boundary `IMAX` (the "boundary zone").
   - Select `MODIFY BNDY`.
   - Select `COUPLE`.
   - Select `SEL OTHER BND`.
   - Pick zone 2, boundary `I1` (the "source zone").
   - Select `SET COUP MODE`.
   - Click on the choice under `CONNECT MODE` (initially `** NONE **`).
   - Respond to the prompts at the bottom of the screen, using `1` (rotation) as the connection mode, a point on the x axis as the center of rotation, and `36.0 0.0 0.0` for the rotation angles.
   - Select `CONNECT`.

   (b) For the next rotation:

   - Select `COUPLE`.
   - Select `SEL OTHER BND`.
   - Pick zone 2, boundary `I1` (the "source zone").
   - Select `SET COUP MODE`.
   - Click on the choice under `CONNECT MODE` (now set to `ROTATION`).
   - Respond to the prompts at the bottom of the screen as before, except using `72.0 0.0 0.0` for the rotation angles.
   - Select `CONNECT`.

   (c) Repeat the previous step for rotation angles of 108°, 144°, 180°, 216°, 252°, 288°, and 324°.

5. Couple the zone 1 `IMAX` surface to the zone 2 `I1` surface in its non-rotated position.

   - Select `BOUNDARY COND`.
   - Pick zone 1, boundary `IMAX` (the "boundary zone").
   - Select `MODIFY BNDY`.
   - Select `COUPLE`.
   - Select `SEL OTHER BND`.
   - Pick zone 2, boundary `I1` (the "source zone").
   - Select `COUPLE`.

6. Repeat steps 4 and 5 twice, coupling the zone 1 IMAX surface to the I1 surfaces in zones 3 and 4.

7. Whew!

The relevant keyword input in the input data (*.dat*) file would be

```
ROTATE 0.0 0.0 0.0 -1680.0 0.0 0.0 ZONE 2:4

REL-ROT-ZONE
   ZONE 1 BOUNDARY IMAX SUBSET I LAST LAST J  1   18 K ALL
   ZONE 2 BOUNDARY I1
   ROTATING-ZONE 2
ENDRRZ
REL-ROT-ZONE
   ZONE 1 BOUNDARY IMAX SUBSET I LAST LAST J 19   34 K ALL
   ZONE 3 BOUNDARY I1
   ROTATING-ZONE 2
ENDRRZ
REL-ROT-ZONE
   ZONE 1 BOUNDARY IMAX SUBSET I LAST LAST J 35 LAST K ALL
   ZONE 4 BOUNDARY I1
   ROTATING-ZONE 2
ENDRRZ
```

See Also: ROTATE

RESTART | START — Begin run in specified zone

```
{START | RESTART} [zone [plane]]
```

This keyword allows the user to specify the zone (and plane, for a marching solution) in which the solution will start (or restart) when running in single-processor mode. In parallel mode, the starting zone number is automatically set to 1.

In both single-processor and parallel modes, if this keyword is not used, Wind-US checks for the existence of a flow (*.cfl*) file. If one exists, the solution will be restarted using the values in the *.cfl* file as initial conditions. If a *.cfl* file does not exist, Wind-US will create and initialize one.

zone First zone entered. If not specified, the solution will begin in the zone after the last successfully completed zone. However, if Global Newton iteration is being used, the solution must start in zone 1, and specification of a *zone* value other than 1 is not allowed.

plane *i*-plane to start/restart solution when running in PNS marching mode. If omitted, Wind-US will automatically start at the next *i*-plane after the last one completed.

RHS — Explicit operator control

Structured Grids

```
RHS scheme [order [modifier]] [ZONE range1[,range2[, ...  rangen]]]
```

Unstructured Grids

```
RHS scheme order CELLCENTERED [ZONE range1[,range2[, ...  rangen]]]
```

This keyword allows control of the explicit operator used within each zone. The parameter *scheme* specifies the general type of differencing scheme, *order* specifies the differencing order, and (for structured grids) *modifier* specifies the type of spatial differencing.

The zone specification format is essentially the same as for a *zone_selector* (see Section 10.2), except that the word `ZONE` is required if a *range* is being input.

Structured Grids

For structured grids, the following choices are available for *scheme*:

`CENTRAL, COAKLEY, HLLE, ROE, ROE_OVER, RUSANOV, VANLEER`

The parameter *order* specifies the differencing order, and must be one of the following:

`FIRST, SECOND, THIRD, FOURTH, FIFTH`

The *modifier* must be one of:

`CENTRAL, UPWIND, PHYSICAL, UPWINDBIASED`

Not all combinations of options are valid.

If *scheme* is `CENTRAL`, second-order central differencing is used, and any values specified for *order* and *modifier* are ignored.

If *scheme* is `COAKLEY`, Coakley differencing is used and the following options are available for *order*. Any *modifier* that is specified is ignored. Following the usual conventions for displaying keyword syntax, optional keyword parameters are inside square brackets. Thus, `RHS COAKLEY` and `RHS COAKLEY SECOND` both give second-order Coakley differencing, fully upwind.

order	Explicit Operator
`FIRST`	First-order, upwind
`[SECOND]`	Second-order, fully upwind
`THIRD`	Third-order, upwind-biased

If *scheme* is `ROE`, `VANLEER`, `HLLE`, or `RUSANOV`, then Roe, Van Leer, HLLE, or Rusanov differencing is used, respectively.

If *scheme* is `ROE_OVER`, an alternative implementation of the Roe scheme from the OVERFLOW code is used. This implementation seems to be faster, and includes an entropy fix that prevents expansion shocks.

The HLLE scheme also includes a built-in entropy fix. Otherwise, the HLLE and Roe schemes give very similar results.

The following options are available for *order* and *modifier* with all of the Roe, Van Leer, HLLE, and Rusanov schemes. Again, optional parameters are inside square brackets. Thus, RHS ROE, RHS ROE SECOND, and RHS ROE SECOND PHYSICAL all give second-order Roe upwind-biased differencing, modified for stretched grids.

order and *modifier*	Explicit Operator
FIRST [UPWIND]	First-order, upwind
FIRST PHYSICAL	First-order, upwind, modified for stretched grids
[SECOND [PHYSICAL]]	Second-order, upwind-biased, modified for stretched grids
SECOND CENTRAL	Second-order, central
SECOND UPWINDBIASED	Second-order, upwind-biased
SECOND UPWIND	Second-order, fully upwind
THIRD [UPWINDBIASED]	Third-order, upwind-biased
THIRD UPWIND	Third-order, fully upwind
FOURTH [UPWINDBIASED]	Fourth-order, upwind-biased
FOURTH CENTRAL	Fourth-order, central
FIFTH [UPWINDBIASED]	Fifth-order, upwind-biased

If the RHS keyword is not used, the second-order upwind-biased Roe scheme with modifications for stretched grids (i.e., RHS ROE SECOND PHYSICAL) is used.

Notes

- Roe zonal coupling requires that Roe, Van Leer, HLLE, or Rusanov differencing be used.
- TVD flux limiting, and the default zonal coupling procedure (high-order Roe), can not be used with some of the higher-order explicit operators. See the TVD and COUPLING keywords for details.
- Some of the explicit operators can not be used in a spatial marching calculation. See the MARCHING keyword for details.
- If a first-order upwind explicit operator modified for stretched grids is used, test option 189 must be set.
- A Roe, Van Leer, HLLE, or Rusanov explicit operator must be used in zones containing holes.
- The ROE_OVER scheme cannot currently be used for multi-species flows.

See Also: COUPLING, MARCHING, TVD, HLLE, ENTROPY FIX, TEST 189

Unstructured Grids

For unstructured grids, the following choices are available for *scheme*:

HLLE, ROE, RUSANOV

The parameter *order* specifies the differencing order, and must be one of the following:

FIRST, SECOND

Note that for unstructured grids, the *modifier* is required, and must be CELLCENTERED.

For unstructured grids, the use of the the RHS keyword is required; it cannot be defaulted. The Rusanov second-order scheme is recommended, especially above about Mach 2.

ROLL — Specify roll about one of the coordinate axes

Structured Grids

```
ROLL {X | Y | Z} rat x1 x2
```

For structured grids, the `ROLL` keyword allows the user to specify roll about one of the coordinate axes.

rat Rotation rate in radians per second

x1, x2 Coordinates of the center of rotation. The coordinates specified by *x1* and *x2* depend on the rotation axis, as shown in the following table:

Rotation axis	*x1*	*x2*
X	y	z
Y	z	x
Z	x	y

Note that in this mode, the calculation is done in inertial space, and the grid is assumed to roll through inertial space at the specified rate. The grid velocity imparts the rotating component. Thus, in order to show the velocity relative to the rotating axes, the roll component of velocity must be subtracted (via the CFPOST post-processing package or another mechanism).

Note also that, unfortunately, unless `ROLL` is used in a true time-accurate mode which moves the grid each time step (not currently available), as well as giving it velocity, the `ROLL` capability neglects the rotational potential energy, and so is not correct for high rotation rates.

With this keyword, the velocity vector must be aligned with the coordinate axis. (To get an angle of attack, rotate the grid in GMAN.)

See Also: `ROTATE`

ROTATE — Perform calculation in a rotating frame of reference

Structured Grids

ROTATE x_{cntr} y_{cntr} z_{cntr} Ω_x Ω_y Ω_z

For structured grids, the ROTATE keyword allows the user to compute the flow in a rotating reference frame. The center of rotation and rotation rates are specified via the arguments:

x_{cntr}, y_{cntr}, z_{cntr} Center of rotation, in grid units

Ω_x, Ω_y, Ω_z Rotation rates about the three Cartesian coordinate axes, in radians/sec

Note: A similar capability is given by the ROLL keyword, in which the grid is rotated about an axis. However, ROLL does the calculation in inertial space, and uses the grid velocity to impart a rotating component. Unfortunately, unless ROLL is run in a true time-accurate mode which moves the grid each time step (not currently available), as well as giving it velocity, the ROLL capability neglects the rotational potential energy, and so is not correct for high rotation rates.

See Also: REL-ROT-ZONE, ROLL, ARBITRARY INFLOW

SCHMIDT — Set the laminar and turbulent Schmidt numbers

Unstructured Grids

`SCHMIDT` *Schl Scht*

This keyword may be used to set the laminar and turbulent Schmidt numbers. The default values are 0.72 and 0.9, respectively.

This keyword only applies to unstructured grids, with frozen or finite-rate chemistry.

SEQUENCE — Grid sequencing control

Structured Grids

```
SEQUENCE nsi nsj nsk [zone_selector]
```

For structured grids, this option allows the user to, in effect, thin the computational grid, thus reducing CPU requirements. It can be used to obtain quick starting solutions for the fine grid. Separate keywords may be used for each zone.

nsi Number of sequencing levels in the *i* direction

nsj Number of sequencing levels in the *j* direction

nsk Number of sequencing levels in the *k* direction

For one sequencing level, every other grid point is used in the calculation. For two sequencing levels, the sequencing process is repeated, resulting in only every fourth grid point being used. And so on. At the end of the run, the solution is interpolated back onto the entire grid to aid in restarting the solution and to provide a continuous field for post-processing.

There are no restrictions on the number of points in the sequenced direction, except that there must be at least five points in the sequenced (i.e., coarse) grid.

SMOOTHING — Add dissipation to explicit operator

```
SMOOTHING [SECOND val1] [FOURTH val2] [SMLIMT val3] [zone_selector]
```

This keyword is used to apply dissipation to the explicit operator.

Structured Grids

For structured grids, the parameters *val1*, *val2*, and *val3* are the second-order smoothing coefficient, the fourth-order smoothing coefficient, and the smoothing limiter, respectively.

If the SMOOTHING keyword isn't used, no smoothing is applied. If the SMOOTHING keyword is used, but without specifying values, the default values listed below are used. (The table also includes a "TVD-like" value for each smoothing parameter.)

Parameter	Default	"TVD-Like" Value
val1	1/4	< 1
val2	1/256	$< 1/32$
val3	0	1

The default values shown in the above table represent a Jameson-type smoothing, and are good for an Euler analysis. For viscous problems, it is recommended that *val1*, *val2*, and *val3* be set equal to 1, 1/64, and 2, respectively.

See Also: BOUNDARY-DAMP, ACCELERATE, TEST 49

Unstructured Grids

For unstructured grids, the parameters *val1*, *val2*, and *val3* are the flux dissipation parameter, the Jacobian dissipation parameter, and the slope limiting parameter, respectively.

For the Roe scheme, the Jacobian dissipation parameter and the slope limiting parameter are applicable. Suggested values at the start of a calculation are

```
FOURTH 1.5 SMLIMT 1.2
```

The SMLIMT value can be increased to about 1.5 as the calculation progresses.

For the Rusanov scheme, all three smoothing parameters are applicable. Suggested starting values are

```
SECOND 0.5 FOURTH 1.5 SMLIMT 2.0
```

The SECOND and SMLIMT values can then be modified to about 0.25 and 4.0 as the calculation progresses.

If the SMOOTHING keyword isn't used, values of 0.5, 1.5, and 2.0 are used for *val1*, *val2*, and *val3*, respectively. However, if the SMOOTHING keyword is used, but without specifying values, *val1*, *val2*, and *val3* are set to levels more appropriate for structured grids. It is therefore recommended that all three values be explicitly specified when unstructured grids are being used.

See Also: ACCELERATE

SPAWN — Run external processes from Wind-US

SPAWN "*process*" [FREQUENCY *freq*] [NOCHECKPOINT]

This keyword allows the user to start (spawn) a process without stopping Wind-US. A process can be any valid Unix script or executable. When a new process is spawned, Wind-US will wait until the spawned process completes before continuing.

Spawned processes will be run in the same directory as Wind-US. For convenience, you may thus want to use the **-runinplace** option with the *wind* script. See the description of the **-runinplace** and **-runroot** options to the *wind* script in Section 8.1 for details about the Wind-US run directory.

The keyword arguments and options are:

process Full path name to the process (must be in quotes, 80 characters max)

freq Frequency for spawning the process. When Newton iteration is used, the frequency is specified in terms of time levels. Otherwise, *freq* is specified in cycles. The default is 1.

Wind-US will tack the current cycle number (even when Newton iteration is used) onto the end of the *process* call for potential use by the process as a parameter.

NOCHECKPOINT By default, Wind-US will update the common flow (*.cfl*) file before spawning the process. NOCHECKPOINT will disable this update. In either case, the checkpoint interval specified by the checkpoint directive in the multi-processing control (*.mpc*) file will be unchanged. (See Section 9.6.)

Up to 32 separate processes may be spawned by using multiple SPAWN keywords. The FREQUENCY and NOCHECKPOINT options may be specified independently for each process.

Note that while a *process* is being executed, Wind-US's input and output files (i.e., the *.lis* file, *.cfl* file, etc.) remain connected to the Fortran units used by Wind-US. Thus, if a *process* runs a program like *resplt* or *cfpost*, these files cannot be used directly as input. Instead, the *process* must copy the needed file(s) to temporary files, and use the temporary files as input.

Example

A common use for the SPAWN keyword, especially for unsteady flows, is to save intermediate *.cfl* files during a Wind-US run. A shell script may be SPAWN'ed at specified intervals to save the file under a unique name.

For example, consider the following shell script, named *save_cfl*.

```
#! /bin/sh
#
# save_cfl - Save intermediate .cfl files.  This script is intended
#            to be spawned during a run using the SPAWN keyword, as
#
#               SPAWN "path-to-script path-to-cfl" FREQUENCY num
#
#            where ’path-to-script’ is the full path name for this
#            script, 'path-to-cfl' is the full path name for the saved
#            .cfl files (the current cycle number will automatically
#            be appended to this name), and 'num' is the frequency for
#            the SPAWN command.  Note that the quote marks around
#            "path-to-script path-to-cfl" must be included.

# Check for enough arguments

if [ $# -lt 2 ]
then
   echo 'Error: save_cfl: Path name for saved .cfl files not specified' >& 2
   echo '       Use SPAWN keyword, as:' >& 2
   echo '       SPAWN "path-to-script path-to-cfl" FREQUENCY num' >& 2
   exit 1
fi

# $1 is path name for the saved .cfl files, $2 is current cycle number

cp FOR020 $1.$2
```

If the above script is located in the directory */home/user/bin*, the SPAWN keyword may be used as follows to save the *.cfl* file every 1000 cycles (assuming a non-Newton run) in the directory */home/user/wind*.

```
SPAWN "/home/user/bin/save_cfl /home/user/wind/runa.cfl" FREQUENCY 1000
```

Since the cycle number is automatically added to the end of the *process* when it's spawned, the above use of the SPAWN keyword causes the *save_cfl* script to be run as

```
/home/user/bin/save_cfl /home/user/wind/runa.cfl ncycle
```

where *ncycle* is the current cycle number. The result is that the intermediate *.cfl* files will be stored in the directory */home/user/wind*, with names *runa.cfl.1000*, *runa.cfl.2000*, etc.

STAGES — Multi-stage time stepping

Structured Grids

```
STAGES ityp [COEFFICIENTS x1 x2 ... xn] [zone_selector]
```

For structured grids, this keyword allows the user to use a Runge-Kutta time stepping option. The parameter *ityp* specifies the number of stages, and *x1 x2 . . . xn* specify the coefficients. The following *ityp* values are available:

ityp	Stages
0	One stage, Euler implicit or explicit
1	Four stage, Jameson type
5	Three stage, minimal storage, third order

The default coefficients are:

ityp	# Req'd	Defaults
0	—	—
1	4	1/4, 1/3, 1/2, 1
5	5	1/4, 8/15, 0, 5/12, 3/4

TDA_INVALID — Rewrite boundary data to *.tda* file

```
TDA_INVALID [ZONE] range1[,range2[, ...  rangen]]
```

This keyword tells Wind-US that the boundary data from the *.tda* file for the specified zone(s) should not be used, until new boundary data is written to the file during the first solution cycle. In the zone specification, the *range* parameter(s) must be one of the following forms:

zonenum	Selects zone *zonenum*
begzone:*endzone*	Selects all zones from *begzone* to *endzone*
ALL	Selects all zones

TEST — Non-production test options

```
TEST number [mode]
```

For purposes of program testing, the user may select one or more test options for any job. These options are selected by the keyword `TEST` (beginning in column 1) followed by one or two integer variables. The keyword and the integer variables must be separated by one or more blanks. The first integer selects the test option. The second integer, which is not mandatory, selects a mode for that option. If the second integer is omitted, a default mode is activated. Any number of valid test options may be selected. However, only one mode may be activated for each option. If an option is selected more than once, the mode identified in the last selection will be used.

The list of valid options and modes is provided in Section 11.

TIMEMARCHING — Time step type and limit

Unstructured Grids

```
TIMEMARCHING [VARIABLE-DT | CONSTANT-DT] [DTRATIO value]
```

This keyword is applicable only to unstructured grids, and sets the type of time step and a maximum limit on the size.

`VARIABLE-DT` A local time step (i.e., varying in space) will be used, with the CFL number specified using the `CFL#` keyword. This is the default, and helps speed convergence for steady-flow problems.

`CONSTANT-DT` A global time step (i.e., constant in space) will be used, with the time step in seconds specified using the `CFL#` keyword. This option is generally used for unsteady flow problems.

The `DTRATIO` *value* is the limit of the maximum to minimum time step size that is allowed when local time stepping is used. The default value is 10^6.

See Also: `CFL#`

TSL | THIN SHEAR LAYER — Thin shear layer option

Structured Grids

```
{TSL | THIN} [SHEAR] [LAYER] word1 word2 word3 [zone_selector]
```

For structured grids, this keyword turns off the viscous terms in specified coordinate directions. The parameters *word1*, *word2*, and *word3* are keywords controlling the viscous terms in the ξ-, η-, and ζ-directions, respectively. They may have the following values:

Keyword	Meaning
`VISCOUS`	Retain all viscous terms in this direction
`INVISCID`	Neglect all viscous terms in this direction

By default, when `INVISCID` is set for a direction, the scalar implicit operator will be used in that direction (the full block implicit operator is used in viscous directions). This may be overridden using the `IMPLICIT` keyword.

TTSPEC — Wall temperature and transition (block)

Structured Grids

```
TTSPEC
   TYPE TEMPERATURE | TRANSITION
   MODE FILE filename | CURRENT
   ZONE zone_number
   SURFACE surfname
   SUBSET ALL
ENDTTSPEC
```

For structured grids, this keyword block allows a point-by-point surface temperature boundary condition to be used, and/or point-by-point boundary layer transition information to be specified. Surface temperature and transition data may be specified for any boundary surface in any zone.[32] The maximum total number of temperature/transition surfaces, combined, is determined by the Fortran parameter `MAXTTS`, currently equal to 20.

The normal procedure is to do an initial run, perhaps with just a few cycles, without specifying temperature/transition information, to create the initial common flow (*.cfl*) file. The temperature/transition data is then created and added to the *.cfl* file using the *tmptrn* utility.

For backward compatibility with early versions of WIND, however, the temperature/transition data may be read from separate ASCII files, one for each applicable surface, created with the older *tmptrn* utility. This would only be necessary during the initial (i.e., non-restart) run, since Wind-US will automatically store the data in the *.cfl* file, where it can be read during subsequent runs.

In addition, in earlier versions of *tmptrn*, the temperature written into the *.cfl* file was in K, instead of being non-dimensionalized. This error was fixed in version 1.8 of *tmptrn*. However, some versions of Wind-US had coding to accomodate the dimensional temperature value, and these versions will not work with temperature distributions written using *tmptrn* 1.8 and above. See the *tmptrn* documentation for details.

The various elements of the `TTSPEC` keyword block are defined as follows:

```
TYPE TEMPERATURE | TRANSITION
```

This keyword indicates whether a surface temperature distribution or boundary layer transition information is being specified.

```
MODE FILE filename | CURRENT
```

This keyword specifies where the surface temperature or transition data is stored.

`FILE` *filename* The data is stored in the ASCII file *filename*, created using the older *tmptrn* utility distributed with early versions of WIND. If *filename* is specified without an extension, an extension of *.dat* is assumed.

This option is included for backward compatibility only, using existing files created with the older *tmptrn* utility, and is only needed for an initial (i.e.,

[32] Note, though, that although Wind-US allows temperature/transition data to be specified on any boundary surface, the *tmptrn* utility used to add the data to the *.cfl* file currently does not allow specification on the i_1 or i_{max} surface.

non-restart) run. Subsequent (i.e., restart) runs should use MODE CURRENT. New applications should use the latest *tmptrn* utility to write the temperature/transition data into the *.cfl* file directly.

CURRENT The data is stored in the flow (*.cfl*) file.

ZONE *zone_number*

This keyword specifies the number of the zone containing the boundary surface along which temperature or transition data is being specified.

SURFACE *surfname*

This keyword specifies the boundary surface in zone *zone_number* along which temperature or transition data is being specified. Currently, the applicable surface names are I1, IMAX, J1, JMAX, K1 and KMAX, corresponding to the i_1, i_{max}, j_1, j_{max}, k_1 and k_{max} surfaces, respectively.

SUBSET ALL

In the future, this keyword will allow temperature/transition information to be specified over a subset of the surface. Currently, SUBSET ALL is only used to update the counter of the number of temperature/transition surfaces, and must be specified once for each surface.

Example

As an example, suppose we are specifying the wall temperature distribution along the j_1 surface in zone 1, and the j_1 and j_{max} surfaces in zone 2. In addition, suppose we're specifying boundary layer transition along the j_1 surface in zone 1. If existing temperature/transition files are being used, created with the older *tmptrn* utility, the TTSPEC keyword block for the initial run might be

```
TTSPEC
   TYPE TEMPERATURE
      ZONE 1
         MODE FILE temp.z1j1.asc
         SURFACE J1
         SUBSET ALL
      ZONE 2
         MODE FILE temp.z2j1.asc
         SURFACE J1
         SUBSET ALL
         MODE FILE temp.z2jm.asc
         SURFACE JMAX
         SUBSET ALL
   TYPE TRANSITION
      ZONE 1
         MODE FILE tran.z1j1.asc
         SURFACE J1
         SUBSET ALL
ENDTTSPEC
```

Since the temperature/transition data will be written into the *.cfl* file during the initial run, later (i.e., restart) runs could use

```
TTSPEC
   TYPE TEMPERATURE
      ZONE 1
         MODE CURRENT
         SURFACE J1
         SUBSET ALL
      ZONE 2
         MODE CURRENT
         SURFACE J1
         SUBSET ALL
         MODE CURRENT
         SURFACE JMAX
         SUBSET ALL
   TYPE TRANSITION
      ZONE 1
         MODE CURRENT
         SURFACE J1
         SUBSET ALL
ENDTTSPEC
```

See Also: WALL TEMPERATURE

TURBULENCE — Turbulence model selection

Structured Grids

```
TURBULENCE [MODEL] model [RC | ROTATION] [F2FIX dmax] [ITERATIONS iter]
    [zone_selector]
```

Unstructured Grids

```
TURBULENCE [MODEL] model [zone_selector]
```

This keyword is used to request an inviscid or viscous solution, and to select a turbulence model for one or more zones.

Structured Grids

For structured grids, the parameter *model* must be one of the following keywords:

`INVISCID | EULER` Inviscid flow

`LAMINAR` Laminar flow

`CEBECI [SMITH]` Cebeci-Smith algebraic turbulence model

`[BALDWIN] LOMAX` Baldwin-Lomax algebraic turbulence model

`PDT` Combination Baldwin-Lomax and P. D. Thomas algebraic shear layer model

`[BALDWIN] BARTH` Baldwin-Barth one-equation turbulence model

`SPALART [ALLMARAS]` Spalart-Allmaras one-equation turbulence model. Additional keywords may be used with the Spalart-Allmaras model to specify the freestream turbulence level (p. 235), and to specify use of the Spalart Detached Eddy Simulation (DES) turbulence model (p. 241).

In multi-zone problems, the Spalart-Allmaras model may not be used with different turbulence models in other zones, other than the Spalart DES model. However, it may be used with inviscid or laminar flow in other zones.

`SST [COMPRESSIBLE]` Two-equation Shear Stress Transport turbulence model. If `COMPRESSIBLE` is specified, the compressibility corrections of Suzen and Hoffmann are applied.

Additional keywords specific to the SST model are available for specifying compressibility correction options (p. 235), and for specifying freestream values of k and ω (p. 236). Other keywords may be used to specify use of a combined SST/LES model using an epsilon limiter (p. 242), or a Nichols-Nelson hybrid model (p. 242).

The compressibility corrections have been found beneficial for free shear layers in flows where the convective Mach number is above about 0.5). The overall effect is to increase the spreading in mixing layers, jets, etc.

In multi-zone problems, the SST model may not be used with different turbulence models in other zones, other than the hybrid SST/LES model. However, it may be used with inviscid or laminar flow in other zones.

`CHIEN [K-E]` Low Reynolds number two-equation k-ϵ turbulence model of Chien.

The user should be aware of additional keywords specific to the k-ϵ models, particulary those used to control initialization, starting on p. 237. Other keywords may be used to specify use of a Nichols-Nelson hybrid Chien/LES model, as described starting on p. 242.

In multi-zone problems, the Chien model may not be used with different turbulence models in other zones, other than the Rumsey-Gatski model and/or a hybrid Chien/LES model. It also may not be used with inviscid or laminar flow in other zones.

`RUMSEY-GATSKI [ASM] [K-E]`

Low Reynolds number two-equation k-ϵ algebraic Reynolds stress model of Rumsey and Gatski.

The user should be aware of additional keywords specific to the k-ϵ models, particulary those used to control initialization, starting on p. 237.

In multi-zone problems, the Rumsey-Gatski model may not be used with different turbulence models in other zones, other than the Chien model. It also may not be used with inviscid or laminar flow in other zones.

Note that with the exceptions noted above for the Spalart, SST, Chien, and Rumsey-Gatski models, different turbulence models, or inviscid or laminar flow, may be specified in different zones. *However, you must specify a "default" turbulence model (or inviscid or laminar flow) in the input data file. Wind-US will stop if you do not.* By "default", we mean without specifying zones.

For example, for a three-zone problem with inviscid flow in zone 1 and the Spalart-Allmaras turbulence model in zones 2 and 3, the following will *not* work, and the code will stop:

```
TURBULENCE INVISCID ZONE 1
TURBULENCE SPALART ZONE 2,3
```

Instead, one could specify the following, which will work:

```
TURBULENCE INVISCID
TURBULENCE SPALART ZONE 2,3
```

Additional parameters that may be used with the `TURBULENCE` keyword are:

`RC | ROTATION` May be used with the Spalart-Allmaras one-equation model to include a correction for system rotation and streamline curvature

`F2FIX` *dmax* May be used with the SST two-equation model to specify a maximum distance from the wall, *dmax*, within which the F_2 term may be non-zero. Beyond that distance, the F_2 term is set to zero. F_2 is a blending function, designed to limit the effects of the shear stress transport term to regions near walls.

`ITERATIONS` *iter* Wind-US organizes the equations to be solved into logical "groups" that are solved together. It also allows multiple iterations of a specific group (i.e., sub-iterations) for each "iteration per cycle". (The number of iterations per cycle is set using the `ITERATIONS` keyword.)

For one- and two-equation turbulence models, this parameter allows the user to request *iter* sub-iterations of the turbulence model equation group for each "iteration per cycle". If `NAVIER-STOKES ITERATIONS` is defaulted, this corresponds to *iter* iterations of the turbulence model equations for each iteration of the mean flow equations.

The default for *iter* is one, indicating that each "iteration per cycle" corresponds to one iteration of the turbulence model equations.

Note that for the one- and two-equation turbulence models, the turbulence model equations may be solved without simultaneously solving the Navier-Stokes equations. Of course, the turbulence variables depend on the mean flow field, so a reasonable mean flow solution must already exist.

As an example, suppose a mean flow solution has been computed using the SST turbulence model. The Chien k-ϵ variables consistent with the existing mean flow field may be computed by restarting from the SST solution, and solving just the Chien k-ϵ equations.

```
ITERATIONS PER CYCLE 2 ZONE ALL
NAVIER-STOKES ITERATIONS 0 ZONE ALL
TURBULENCE MODEL CHIEN ITER 5 ZONE ALL
```

The above keywords specify that, for all zones, there will be two iterations per cycle, with no Navier-Stokes sub-iterations and five Chien model sub-iterations for each "iteration per cycle". There will thus be a total of ten iterations of the Chien k-ϵ equations in each zone prior to completing a cycle and exchanging information between zones.

See Also: `ITERATIONS`, `NAVIER-STOKES ITERATIONS`, `TEST 21`, `TEST 67`

Spalart-Allmaras Model

```
FREE_ANUT anutinf
```

When `TURBULENCE SPALART` is specified, indicating use of the Spalart-Allmaras model, the separate keyword `FREE_ANUT` may be used to specify the freestream value of the eddy viscosity ν_t. The default value is 5.0.

SST Model

Compressibility Correction Options

```
COMPRESSIBLE [DISSIPATION] {ON|OFF} [zone_selector]
PRESSURE [DILATATION] {ON|OFF} [zone_selector]
```

If `TURBULENCE SST COMPRESSIBLE` is specified, indicating that the SST model is to be used with the compressibility corrections of Suzen and Hoffmann, the separate keywords `COMPRESSIBLE` and `PRESSURE` may also be specified. The `COMPRESSIBLE` keyword controls whether or not a compressible dissipation correction is used, and the PRESSURE keyword controls whether or not the pressure dilatation term is included. Both of these are ON by default.

Specifying Freestream k and /omega

```
FREE_K val_k
FREE_OM val_om
```

If TURBULENCE SST is specified, indicating that the SST model is to be used, the separate keywords FREE_K and FREE_OM may be used to input dimensional freestream values of k and ω. The following options are possible:

$val\_k > 0$ The turbulent kinetic energy k and the specific dissipation rate ω are specified directly, with

$$k = val\_k \ (\text{ft}^2/\text{sec}^2)$$
$$\omega = val\_om \ (1/\text{sec})$$

The turbulent viscosity ν_t is then equal to k/ω.

$val\_k < 0$ The turbulence intensity is set equal to $|val\_k|$, expressed as a percentage of the freestream velocity U_∞. Thus, the turbulent kinetic energy is computed as

$$k = 1.5(0.01 \, |val\_k| \, U_\infty)^2$$

The turbulent viscosity ν_t is automatically set equal to $0.001\nu_l$, where ν_l is the laminar viscosity, and the specific dissipation rate is computed as $\omega = k/\nu_t$.

$val\_om < 0$ The specific dissipation rate ω is set equal to *val_om* percent of U_∞/L_{ref}, where U_∞ is the freestream velocity, and L_{ref} is the reference length from the grid (*.cgd*) file. Thus

$$\omega = 0.01 \, |val\_om| \, \frac{U_\infty}{L_{ref}}$$

The turbulent viscosity ν_t is set to the same percentage of the laminar viscosity.

$$\nu_t = 0.01 \, |val\_om| \, \nu_l$$

The turbulent kinetic energy is then computed as $k = \omega\nu_t$.

The default, and recommended, values are

$$\omega = 10U_\infty/L$$
$$k = \omega\nu_t$$

where the freestream turbulent viscosity ν_t is arbitrarily set to $0.001\nu_l$.

Note that

- If $val\_k > 0$, a positive value must be specified for *val_om*.
- If $val\_k \leq 0$, *val_om* should not be specified.
- If $val\_om < 0$, any value specified for *val_k* is ignored.

Inflow turbulence levels may be specified for the SST model in the ARBITRARY INFLOW keyword block. If this is done, the TURBULENCE keyword must come before the ARBITRARY INFLOW keyword block in the input data (*.dat*) file.

See Also: ARBITRARY INFLOW

Chien and Rumsey-Gatski k-ϵ Models

Several keywords may be used with the Chien and Rumsey-Gatski k-ϵ models to control the initialization procedure, enhance their stability, and improve their accuracy in adverse pressure gradients and at high Mach numbers.[33] For convenience, all keyword phrases associated with the k-ϵ models begin with K-E.

```
K-E INITIALIZE [FROM] {EXISTING | EQUILIBRIUM | FREESTREAM}
```

This keyword determines how the turbulent transport variables (k, ϵ, and μ_t) for the k-ϵ models will be initialized.

It is recommended that the user first obtain an intermediate solution using another turbulence model, before switching to one of the k-ϵ models. Initializing from an existing turbulent solution rather than uniform values aids somewhat in convergence and improves the stability of the models by reducing the dramatic changes in turbulence values that occur during the first few iterations after initialization.

This intermediate solution need not be fully converged, but should have reached a state where the the turbulence is well established within the shear regions (boundary layers, mixing layers, etc.) of each zone. Users can examine values of mut/muinf with CFPOST to check the state of turbulence in the flow prior to switching models. Low values of mut/muinf (say < 50 or 100) may be insufficient to sustain turbulence, causing the solution to relaminarize as additional cycles are performed. The SST and Spalart models are good choices for obtaining the intermediate solution.

There are three methods for establishing the initial values for the k-ϵ models.

The first method, given by the EXISTING parameter, performs an "intelligent" initialization, based on the type of turbulence model used in the previous run. This is the default. When initializing from another two-equation model, direct conversion of turbulence values is performed. For lower-order models, the procedure is equivalent to using the EQUILIBRIUM parameter. When initializing from inviscid or laminar solutions, the procedure is equivalent to using the FREESTREAM parameter.

The second method, given by the EQUILIBRIUM parameter, uses an assumption of turbulent equilibrium, namely that the production, Π, of turbulent kinetic energy equals the rate of dissipation, together with an existing turbulent viscosity profile to initialize the k and ϵ variables.

$$\rho\epsilon = \Pi/Re$$
$$\rho k = \sqrt{\frac{\rho\epsilon\mu_t}{C_\mu f_\mu Re}}$$

The third method, given by the FREESTREAM parameter, initializes the turbulence variables to

[33] The material in this section was originally written by Dennis Yoder of NASA Glenn Research Center.

uniform values within each zone.

$$
\begin{aligned}
\rho k &= \rho k_\infty \\
\rho \epsilon &= \rho \epsilon_\infty \\
\mu_t &= (\mu_t)_\infty
\end{aligned}
$$

where the local density is used and the freestream conditions k_∞ and $(\mu_t)_\infty$ may be specified with the keywords K-E FREE_K and K-E FREE_MUT. This method is generally less successful than the others.

```
K-E FREE_K val1
K-E FREE_MUT val2
```

These keywords may be used to specify the freestream turbulence values to be used when initializing the turbulence variables to uniform values (i.e., with the K-E INITIALIZE FREESTREAM keyword). The interpretation of the input depends on the signs of *val1* and *val2*.

For the turbulence kinetic energy k_∞,

$$
k_\infty = \begin{cases} \frac{3}{2} I^2 u_\infty^2 & \text{for } \textit{val1} < 0\text{, and where } |\textit{val1}| = I \\ \bar{k}_\infty / \bar{a}_\infty^2 & \text{for } \textit{val1} > 0\text{, and where } \textit{val1} = \bar{k}_\infty \text{ (ft/sec)}^2 \end{cases}
$$

and for the turbulent viscosity $(\mu_t)_\infty$,

$$
(\mu_t)_\infty = \begin{cases} (\mu_t)_\infty & \text{for } \textit{val2} < 0\text{, and where } |\textit{val2}| = (\mu_t)_\infty \\ (\bar{\mu}_t)_\infty / \bar{\mu}_\infty & \text{for } \textit{val2} > 0\text{, and where } \textit{val2} = (\bar{\mu}_t)_\infty \text{ (slug/ft-sec)} \end{cases}
$$

where the overbar denotes a dimensional value.

If the K-E FREE_K keyword is not used, or if $\textit{val1} = 0$, then a default value of $\textit{val1} = -0.01$ is used, which corresponds to a turbulence intensity I of 1%. If the K-E FREE_MUT keyword is not used, or if $\textit{val2} = 0$, then a default value of $\textit{val2} = -0.001$ is used. This sets the freestream turbulent viscosity to be 0.001 times the freestream laminar viscosity. Note that for values greater than zero, the expected units for *val1* and *val2* are $(\text{ft/s})^2$ and slug/ft-s, respectively.

These freestream values are only used when the k-ϵ model is initialized from uniform conditions. Currently, the model extrapolates to get values at all inflow and outflow boundaries. Thus, K-E FREE_K and K-E FREE_MUT can not be used to specify inflow conditions.

```
K-E REINITIALIZE
```

This keyword signals the code to ignore the old k-ϵ information in the flow (*.cfl*) file and perform a fresh initialization from uniform values. This command must be removed on subsequent runs or else the model will reinitialize itself each time. Under normal operation, this keyword should not be used.

```
K-E LINEARIZATION APPROXIMATE | FULL
```

This keyword controls the implicit treatment of the k-ϵ source terms. The APPROXIMATE formulation results in greater diagonal dominance by neglecting coupling of the k and ϵ equations. The key formulation includes the coupling terms. The default is APPROXIMATE.

```
K-E [TVD] ORDER {1|2|3}
```

This keyword sets the spatial order of accuracy of the TVD upwinding used in solving the k-ϵ equations. The default is first order.

```
K-E RELAX [FOR] val [ITERATIONS]
```

Updated values of k, ϵ, and μ_t will be relaxed for *val* iterations (the default is 500) following the initialization. Relaxation of each of these variables reduces the amount they may change during any single iteration. Immediately after initialization, the allowed changes are significantly reduced. This restriction is then gradually lifted as the last relaxation iteration is approached.

```
K-E [MAXIMUM] [TURBULENT] VISCOSITY val1
K-E [TURBULENT] [REFERENCE] VELOCITY val2
```

The k-ϵ model uses limiters within the interior of each zone to increase convergence and stability by capping the values of the turbulence quantities at both the high and low extremes. This is usually only necessary during the first few iterations after initialization, when the fluctuations in k and ϵ tend to be the most dramatic.

Nondimensional values of the minimum limiters have been preset to small numbers. k_{min} is set to 10^{-10}, ϵ_{min} is set to 10^{-12}, and $(\mu_t)_{min}$ is computed from the turbulent viscosity relation using an assumed reference density of 1, $C_\mu = 0.09$, and $F_\mu = 1$.

The above keywords determine the maximum limiting values for the turbulence quantities. The first keyword sets the maximum turbulent viscosity to be *val1* (the default is 10,000) times the freestream viscosity. The second keyword sets the turbulent reference velocity equal to *val2* (the default is 1.0) times the freestream speed of sound. The maximum turbulent kinetic energy allowed is 10% of the kinetic energy of the turbulent reference velocity:

$$k_{max} = 0.10 \frac{u^2_{ref(k\text{-}\epsilon)}}{2}$$

The maximum dissipation rate is again computed from the turbulent viscosity relation.

The use of these limiters can be summarized as follows:

- If k or ϵ falls below its preset minimum value, it is reset to the minimum value. This typically occurs in the freestream.
- If the turbulent kinetic energy exceeds k_{max}, it is capped at this value. The dissipation rate is taken to be the larger of the current dissipation rate or ϵ_{max}.
- If the turbulent viscosity exceeds $(\mu_t)_{max}$, it is capped at this value and the turbulent kinetic energy is recomputed from the turbulent viscosity relation. The turbulent dissipation rate is left unchanged.

If the maximum limiters cause the turbulence variables to be capped within the flowfield, a warning message will be written to the list output (*.lis*) file during the final cycle. By using CFPOST to examine the normalized variable `mut muinf`, one can observe where these limiters are being used and adjust them using the above keywords. It is important that the turbulence values not be limited upon convergence.

K-E COMPRESSIBILITY [CORRECTION] {NONE | OFF | SARKAR | WILCOX | USER α_k M_{t_0}}

This keyword may be used to specify a compressibility correction, designed to enhance predictions at higher Mach numbers. The equation for the compressibility correction is

$$F(M_t) = \alpha_k \max\left(M_t^2 - M_{t_0}^2, 0\right)$$

The turbulent Mach number M_t is defined from $M_t^2 = 2k/a^2$, where a is the local speed of sound.

The parameters α_k and M_{t_0} for the various options are defined in the following table.

Correction Type	α_k	M_{t_0}
NONE | OFF	0.0	0.00
SARKAR	1.0	0.00
WILCOX	1.5	0.25

Note that both NONE and OFF disable the compressibility correction, and that values of α_k and M_{t_0} should only be included when using the USER option. The default is OFF.

Both the Sarkar and Wilcox compressibility corrections are designed to improve the prediction of compressible jet flows by including the compressible portion of the dissipation rate in the transport equation for the turbulent kinetic energy. These corrections use simple algebraic relations between the solenoidal and compressible dissipation rates. The effect of these corrections is to reduce the turbulent kinetic energy in regions where the flow is supersonic. In terms of supersonic jet predictions, this results in slower spreading rates, reduced mixing, and a longer core length.

K-E [VARIABLE] CMU {ON|OFF}

It is well known that the baseline k-ϵ model is poorly suited to adverse pressure gradient flows, such as those found in diffusers. Rodi and Scheuerer (1986) demonstrated that for these types of flows, the rate of dissipation near solid boundaries is too small relative to the rate of production of turbulent kinetic energy. This causes the model to overpredict skin friction and predict flows to be attached when experimental results show them to be separated.

The variable C_μ formulation, which is derived from algebraic stress modeling, is designed to help remedy this problem by reducing the turbulent viscosity in regions of the flowfield where the production of turbulent kinetic energy is significantly larger than the rate of dissipation. The specific formulation used is:

$$C_\mu = \min\left(0.09, \frac{0.10738(0.64286 + 0.19607R)}{\left[1 + 0.357(R-1)\right]^2}\right)$$

As the ratio R of production to dissipation increases above 1, the coefficient C_μ is reduced from its normal value of 0.09 to limit the turbulent viscosity.

The variable C_μ option can provide added stability to the k-ϵ model, such as in the case of an airfoil, where the sudden deceleration of the flow near the leading edge would otherwise result in a significant rate of production. In regions of the flow where the turbulence is in equilibrium, i.e., where the production and dissipation are balanced, the turbulent viscosity remains unchanged.

The above keyword may be used to turn this option on or off (the default is `OFF`) for the Chien k-ϵ model It has no effect for the Rumsey-Gatski k-ϵ model.

`K-E CMUMIN` *val*

This keyword controls the lower limit of the C_μ coefficient used in the Rumsey-Gatski model. As part of the algebraic Reynolds stress formulation C_μ varies throughout the flowfield with typical values in the range [0.07, 0.19]. The default value for this limiter is 0.0005, as recommended by Rumsey.

See Also: `TEST 29`, `TEST 51`

Combined RANS/LES Models

The idea behind combined RANS/LES (Reynolds-Averaged Navier Stokes / Large Eddy Simulation) turbulence models is to improve predictions of complex flows in a real-world engineering environment, by allowing the use of LES methods with grids typical of those used with traditional Reynolds Averaged Navier Stokes models. The combined model reduces to the standard RANS model in high mean shear regions (e.g., near viscous walls), where the grid is refined and has a large aspect ratio unsuitable for LES models. As the grid is traversed away from high mean shear regions, it typically becomes coarser and more isotropic, and the combined model smoothly transitions to an LES model.

Three different combined RANS/LES models are available in Wind-US. The first is the Spalart DES model, used in conjunction with the Spalart-Allmaras model. The second may be used with the SST model, and is implemented using a limiter on ϵ. The third is the hybrid model of Nichols and Nelson, which may be used with both the SST and the Chien k-ϵ models.

The combined models may only be used for unsteady flows (i.e., the time step is a constant). They are zonal, however, so you can use a combined model in time-accurate mode in one zone, while using a standard RANS model in steady-state mode in the other zones. For example, a three-zone problem could use the standard SST model with a specified CFL number in zones 1 and 2, and the combined SST/LES model (implemented using an ϵ limiter) with a specified time step in zone 3, using the following keywords:

```
TURBULENCE SST
LESB ZONE 3
CFL# 1.3
TIMESTEP SECONDS 5.0E-6 ZONE 3
```

This capability can accelerate the solution convergence tremendously, especially for large configurations (10 to 20 million grid points) that would be impossible to run in time-accurate mode throughout the flow field.

Spalart DES Model

`DES [CDES` *cdes*`] [`*zone_selector*`]`

When `TURBULENCE SPALART` is specified, the separate keyword `DES` may also be input to use the Spalart Detached Eddy Simulation (DES) turbulence model. It is intended to improve the results for unsteady and massively separated flows. The DES model reduces to the standard Spalart-Allmaras model near viscous walls, where the grid is refined and has a large aspect ratio, but acts like a Large

Eddy Simulation (LES) model away from the boundary, where the grid is coarser and has an aspect ratio of order one.

The input parameter *cdes* specifies the value of the coefficient C_{des} in the model. The default value is 0.65. Increasing C_{des} increases the size of the region in which the DES model reduces to the standard Spalart-Allmaras model. Details may be found in papers by Spalart, Jou, Strelets, and Allmaras (1997) and by Shur, Spalart, Strelets, and Travin (1999).

SST with ϵ Limiter

```
LESB [CBLES cb] [zone_selector]
```

The `LESB` keyword may be used with the SST model (`TURBULENCE SST`) to specify use of a combined SST and LES turbulence model, using an ϵ limiter.

The input parameter *cb* specifies the value of the coefficient C_B in the model. The default value is 10.0. Increasing C_B increases the size of the region in which the combined model reduces to the standard SST model.

Nichols-Nelson Hybrid Model

```
HYBRID [VERSION ver] [CLES cles] [DELTA grid_scale] [zone_selector]
```

The `HYBRID` keyword may be used with either the SST or the Chien k-ϵ model to specify use of the Nichols-Nelson hybrid RANS/LES turbulence model (Nichols and Nelson, 2003).

ver A flag indicating the version of the model to be used.

1 The original Nichols-Nelson hybrid model. The μ_t value from the RANS model is used in the turbulence model equations, and the hybrid μ_t value is used in the Navier-Stokes equations.

2 The hybrid μ_t value is used in both the turbulence model and Navier-Stokes equations.

3 The hybrid μ_t value is used in both the turbulence model and Navier-Stokes equations, but k is treated like a sub-grid kinetic energy, not the full turbulent kinetic energy. (I.e., the model becomes more of an LES subgrid model.)

The default value is 1.

cles The coefficient $c_{\rm LES}$ used when calculating the LES value of the turbulent viscosity.

$$(\mu_t)_{\rm LES} = c_{\rm LES}\,\rho\,\delta\,k^{1/2}$$

The default value is 0.0854.

grid_scale A flag indicating the version of the model to be used.

1 $\delta = \max(dx, dy, dz)$

2 $\delta = \text{volume}^{1/3}$

The default value is 1.

Unstructured Grids

For unstructured grids, the parameter *model* must be one of the following keywords:

`INVISCID | EULER` Inviscid flow

`LAMINAR` Laminar flow

`SPALART [ALLMARAS]` Spalart-Allmaras one-equation turbulence model. Additional keywords may be used with the Spalart-Allmaras model to specify the freestream turbulence level (p. 243).

In multi-zone problems, the Spalart-Allmaras model may not be used with different turbulence models in other zones. However, it may be used with inviscid or laminar flow in other zones.

`POINTWISE` Goldberg pointwise one-equation turbulence model.

In multi-zone problems, the Goldberg pointwise model may not be used with different turbulence models in other zones. However, it may be used with inviscid or laminar flow in other zones.

Note that you must specify a "default" turbulence model (or inviscid or laminar flow) in the input data file. Wind-US will stop if you do not. By "default", we mean without specifying zones.

For example, for a three-zone problem with inviscid flow in zone 1 and the Spalart-Allmaras turbulence model in zones 2 and 3, the following will *not* work, and the code will stop:

```
TURBULENCE INVISCID ZONE 1
TURBULENCE SPALART ZONE 2,3
```

Instead, one could specify the following, which will work:

```
TURBULENCE INVISCID
TURBULENCE SPALART ZONE 2,3
```

Spalart-Allmaras Model

`FREE_ANUT` *anutinf*

When `TURBULENCE SPALART` is specified, indicating use of the Spalart-Allmaras model, the separate keyword `FREE_ANUT` may be used to specify the freestream value of the eddy viscosity ν_t. The default value is 5.0.

`MAX_WALL_DISTANCE` *DistMax*

This keyword may be used with unstructured grids to specify the maximum distance from the wall that will be used in the Spalart-Allmaras model. The value *DistMax* is in grid units (i.e., the same units that are used in the *.cgd* file). The default is $10/Re^{1/5}$, empirically equal to about 25 times the boundary layer thickness for incompressible turbulent flow past a flat plate at $x = L_{\text{ref}}$, where L_{ref} is the reference length.

TVD — Total Variation Diminishing operator flag

Structured Grids

```
TVD [OFF | FACTOR factor | MINMOD [factor] | KOREN [factor] | ALBADA] \
    [zone_selector]
```

This keyword controls the TVD flux limiter in the explicit operator for structured grids, which is helpful in preventing overshoots in flowfield properties in regions of high gradients. TVD may be used with the Coakley, Roe, Van Leer, HLLE, and Rusanov explicit operators. TVD is enabled by default for these operators, using the standard minmod TVD limiter with the default compression parameter, and disabled for all others.

`OFF` Disables TVD for the specified zone(s)

`FACTOR` Use the standard minmod TVD limiter. The value of *factor* specifies the "compression" parameter for the TVD algorithm, which controls the amount of limiting applied.

`MINMOD` Use the standard minmod TVD limiter. This is the same as `FACTOR`, except that the *factor* may be defaulted. The value of *factor* specifies the "compression" parameter for the TVD algorithm, which controls the amount of limiting applied. The default compression parameter is the maximum value which assures TVD properties for the explicit operator being used (as specified by the `RHS` keyword).

For the Coakley explicit operator, the default compression parameter is 0 (i.e., not applicable) for first-order upwind, and 2 for both second-order fully upwind and third-order upwind-biased differencing.

For the Roe, Van Leer, HLLE, and Rusanov explicit operators, the default compression parameter is shown in the following table for the various versions of the operator.

Explicit Operator	*factor*
First-order, upwind	0 (i.e., not applicable)
First-order, upwind, modified for stretched grids	2
Second-order fully upwind	2
Second-order central	2
Second-order upwind-biased	3
Second-order upwind-biased, modified for stretched grids	3
Third-order upwind-biased	4
Third-order fully upwind	Not available
Fourth- and fifth-order	Not available

`KOREN` Use the Koren TVD limiter. With this limiter, the default value of *factor* is 1.0, and does not depend on the explicit operator being used.

`ALBADA` Use the van Albada TVD limiter. With this limiter, no *factor* value is input.

If TVD flux limiting is turned on for an invalid explicit operator, including the "not available" Roe, Van Leer, HLLE, and Rusanov operators, an error message is generated and the run will abort.

See Also: `BOUNDARY TVD`, `RHS`

VISCOSITY — Specification of viscosity law

Structured Grids

```
VISCOSITY {SUTHERLAND | WILKE | KEYE | CONSTANT vis | TUNNEL9 | CUSTOM c1 c2}
```

Unstructured Grids

```
VISCOSITY {SUTHERLAND | WILKE}
```

This keyword allows you to specify the method of computing the transport properties.

The equations shown below are for the laminar viscosity coefficient μ. For all the options except `WILKE`, in Wind-US the laminar thermal conductivity coefficient k is equal to the viscosity coefficient, when non-dimensionalized. For `WILKE`, the form of the equations used for k is the same as those used for μ, but with different constants from the chemistry data (*.chm*) file.

In all of the equations, μ is in slug/ft-sec and T is in °R.

Structured Grids

`SUTHERLAND` Use Sutherland's law, designed for ideal gases with $T > 180$ °R, as follows:

$$\mu = 2.329 \times 10^{-8} \frac{T^{3/2}}{T + 216}$$

This is the default.

`WILKE` Use Wilke's law, designed for multi-species flow (real gases). First, the viscosity coefficient is computed for each individual species n using Sutherland's law, as follows:

$$\frac{\mu_n}{\mu_0} = \left(\frac{T}{T_0}\right)^{3/2} \frac{T_0 + S}{T + S}$$

where T is the local static temperature, and μ_0, T_0, and S are constants read from the chemistry data (*.chm*) file for species n. For N total species, the individual viscosity coefficients are combined using

$$\mu = \sum_{i=1}^{N} \frac{X_i \mu_i}{\sum_{j=1}^{N} X_j \phi_{i,j}}$$

where $\phi_{i,j}$ is a mixing coefficient computed as

$$\phi_{i,j} = \left[8\left(1 + \frac{M_i}{M_j}\right)\right]^{-1/2} \left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{1/2} \left(\frac{M_j}{M_i}\right)^{1/4}\right]^2$$

X is the species mole fraction, and M is the species molecular weight.

`KEYE` Use Sutherland's law for $T \geq 180$ °R, Keyes' law for $T \leq 160$ °R, and a linear combination for 160 °R $< T <$ 180 °R. Sutherland's law is written as above. Keyes' law is given by:

$$\mu = 2.32 \times 10^{-8} \frac{T^{1/2}}{1 + (220/T) \times 10^{-9/T}}$$

And the linear combination is given by

$$\mu = f\mu_S + (1 - f)\mu_K$$

where μ_S and μ_K are the viscosity coefficients from Sutherland's and Keyes' laws, and $f = (T - 160)/20$.

`CONSTANT` *vis* Use a constant molecular viscosity of *vis* (slug/ft-sec)

`TUNNEL9` Use a viscosity model obtained from AEDC Tunnel 9 for nitrogen.

$$\mu = \begin{cases} 8.913 \times 10^{-10}\, T^{\,0.979} & \text{for } T \leq 227 \text{ °R} \\ 2.144 \times 10^{-8}\, T^{\,3/2}/(T + 179.1) & \text{for } 227 \text{ °R} < T \leq 795 \text{ °R} \\ 6.050 \times 10^{-9}\, T^{\,0.659} & \text{for } T > 795 \text{ °R} \end{cases}$$

`CUSTOM` c_1 c_2 Use Sutherland's law with the constants c_1 and c_2, as follows:

$$\mu = c_1 \frac{T^{3/2}}{T + c_2}$$

Unstructured Grids

For unstructured grids, only Sutherland's and Wilke's laws are available. The equations are the same as shown above for structured grids.

VORTEX GENERATOR — Vortex generator model (block)

Structured Grids

```
VORTEX [GENERATOR]
   ZONE iz1 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
        [SUBSET I range J range K range]
   ZONE iz2 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
        [SUBSET I range J range K range]
   NUMBER ival
     vg_boundary {XLOC xl | YLOC yl | ZLOC zl} chord height alpha \
        [VEL vmax] [DEL delta] ENDVORTEX
```

This keyword block is applicable to three-dimensional cases with structured grids, and enables the user to specify a discontinuous change in secondary velocity across a zone boundary in order to simulate the vortices produced by an array of vane-type vortex generators. A vortex generator array consists of one or more vortex generators mounted on viscous wall boundaries. A separate vortex generator keyword block must be used for each array. The model is only applicable to generators placed on viscous wall boundaries. It is the user's responsibility to check this — Wind-US currently has no mechanism for flagging this input error.

The vortex generator model determines the strength of each vortex based on the generator chord length, height and angle of incidence with the incoming flow, as well as the incoming flow core velocity and boundary layer thickness. Each vortex center is placed at the grid point closest to the location determined by the user-specified generator location on the boundary, and the generator height.

Note that the vortex generator model is derived from experimental data taken at axial stations which were one chord length downstream of the trailing edge of the generators, and therefore the secondary velocities produced by the model simulate vortices at this station, rather than at the generator trailing edges. For most accurate results, the boundary where the vortex generator boundary condition is applied should be at this one chordlength station.

The following restriction applies:

- The `BOUNDARY TVD FACTOR 0` keyword option should be used at all interface boundaries containing vortex generators.

The various elements of the `VORTEX GENERATOR` input block are defined as follows:

```
VORTEX [GENERATOR]
```

Defines the beginning of the vortex generator keyword input block.

```
ZONE iz1 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
     [SUBSET I range J range K range]
ZONE iz2 BOUNDARY {I1 | IMAX | J1 | JMAX | K1 | KMAX} \
     [SUBSET I range J range K range]
```

These two lines define the location of the vortex generator array. The relevant zones are given by the values of *iz1* and *iz2*, and the relevant boundaries within zones *iz1* and *iz2* are specified via the `BOUNDARY` keyword parameter.

iz1 The “upstream” zone. The secondary velocities will be increased when passing information from this zone to *iz2*.

iz2 The “downstream” zone, i.e., the zone receiving increased secondary velocities from zone *iz1*. Secondary velocities will be decreased when passing information from this zone back to zone *iz1*.

Note: Currently, the vortex generators must be located at either an i_1 or i_{max} boundary. Thus, the only valid choices with the `BOUNDARY` keyword parameter are `I1` and `IMAX`.

Note that the secondary velocity is the flow in a plane normal to the primary velocity. For example, for a vortex generator array at an i-interface boundary, the primary flow is in the i direction, and the secondary velocity is in the j and k directions.

The `SUBSET` parameter may be used to specify that the change in secondary velocity occurs only over a part of the zone boundary. Otherwise, it is assumed that the change occurs over the entire boundary. The *range* parameters define the part of the zone boundary over which the change occurs, and take one of the following forms:

index1 index2 Starting and ending indices in the specified direction. `LAST` may be used for the last index.

`ALL` Equivalent to `1 LAST`.

The starting and ending indices for the appropriate `I`, `J`, or `K` parameter (depending on the boundary specified) must be the same, and correspond to that boundary.

```
NUMBER ival
```

This defines the number of vortex generators in the vortex generator array (i.e., on the specified boundary).

```
vg_boundary {XLOC xl | YLOC yl | ZLOC zl} chord height alpha \
   [VEL vmax] [DEL delta]
```

Defines the location and geometric parameters of each vortex generator. A separate line of input *must* be included for each generator.

vg_boundary The minimum or maximum index, specified as `IM`, `IX`, `JM`, `JX`, `KM`, or `KX`, within the specified boundary surface (as specified by `ZONE` and `SUBSET`) where the generator is mounted. This boundary must have been defined as a viscous wall in GMAN. As an example, for a vortex generator array at an i-interface boundary, either `JM`, `JX`, `KM`, or `KX` should be specified, where `JM` means the generator is at the $j = 1$ interface boundary, `JX` means it’s at the $j = j_{max}$ boundary, etc.

`XLOC, YLOC, ZLOC` *xl*, *yl*, or *zl* is the x, y, or z coordinate location in inches of the base of the vortex generator on the already specified boundary surface and wall boundary. (Currently, only one coordinate direction and location may be specified. This may lead to ambiguity in specifying the locations for generators placed in complex duct geometries. This shortcoming will be addressed in future code updates.)

chord The chord length of the vortex generator in inches. Must be greater than zero.

height The height of the vortex generator in inches. Must be greater than zero.

alpha The angle of incidence of the generator in degrees. Must be non-zero. More specifically, it is defined as the angle the generator chord line makes with the primary flow direction. The sign of *alpha* is determined using the "right-hand rule" of vector mechanics. For a given generator, use a normal vector pointing into the wall (the thumb), and the primary flow direction (fingers). If the rotation from the primary flow direction towards the generator follows the right-hand rule, then the sign of *alpha* is positive. Otherwise, it is negative. A positive value of *alpha* generally results in a vortex with a counterclockwise rotation, and conversely. The recommended range of magnitudes for *alpha* is between 8 and 20 degrees.

`VEL` *vmax* is the maximum velocity at the vortex generator station, in ft/sec. The default is for Wind-US to compute this value from the flow. It is currently recommended that this value be specified by the user. Must be greater than zero.

`DEL` *delta* is the boundary layer thickness of the incoming flow, in inches. The default is for Wind-US to compute this value from the flow. It is currently recommended that this value be specified by the user. Must be greater than zero.

In selecting values for the above described parameters, keep in mind that the vortex generator model was derived from conservation of momentum and inviscid theory, correlated with experimental data having *height*/*chord* ratios between 0.13 and 2.62, *height*/*delta* ratios between 0.12 and 2.60, and for duct flows with core Mach numbers ranging from 0.20 to 0.60. Because of the theory used in its derivation, the model is intended to work well outside of the range of the experiments. However, there is one caveat: past experience indicates that the model does not work when the vortex generators are placed in regions of sonic flow.

```
ENDVORTEX
```

Ends the vortex generator input block

Example

The following example illustrates the use of the `VORTEX GENERATOR` input block for one vortex generator array located between zones 2 and 3. The interface between zones 2 and 3 corresponds to the i_{max} boundary of zone 2 and the i_1 boundary of zone 3. The array contains two vortex generators, both mounted on the j_{max} viscous wall boundary of the zone interface with z coordinate values of -0.52 inches and 0.52 inches. The generators have the same geometric parameters: the chord length is 1.6 inches, the height is 0.4 inches, and the angle of incidence is 16 degrees.

```
VORTEX GENERATOR
  ZONE 2 BOUNDARY IMAX
  ZONE 3 BOUNDARY I1
  NUMBER 2
    JX ZLOC -0.52 1.6 0.4 16.0
    JX ZLOC  0.52 1.6 0.4 16.0
ENDVORTEX
```

See Also: BOUNDARY TVD

WALL FUNCTION — Specify the use of wall functions

```
WALL FUNCTION {ON|OFF} [zone_selector]
```

For turbulent flows, this keyword may be used to invoke wall function boundary conditions on viscous walls, using the White-Christoph law of the wall. Wall function boundary conditions allow calculations to be performed with fewer grid points, and generally with higher CFL numbers.

A wall function boundary must lie on one of the boundaries of the selected zone, and may be an overlapped or internal boundary. The first grid point adjacent to the boundary must be within the log layer (roughly $15 < y^+ < 100$). The recommended y^+ value at the first point off the wall is about 50. The boundary condition will revert to a no-slip condition when the first grid point off the wall falls below $y^+ = 15$, indicating that it is within the laminar sublayer.

Note that the wall function boundary condition is used to eliminate the grid points that would otherwise be required to resolve the laminar sublayer and the logarithmic layer. The grid beyond the first point off the wall should be the same as for a run without wall functions, in order to properly resolve the rest of the boundary layer. For structured grids, the *cfsubset* utility may be useful when modifying an existing grid for use with wall functions.

The implementation of wall functions in Wind-US involves only the modification of the wall flux, and does not reset the values of any flow quantities.

Viscous forces on wall function boundaries calculated using the `LOADS` keyword should only be used for determining convergence. For structured grids, correct values can be calculated from the *.cfl* file using the integrate force command in CFPOST.

Based on limited test cases, the use of wall functions is not recommended if accurate predictions of wall heat transfer are required, or for flows with strong shock waves.

WALL SLIP — Iterations until no slip

Structured Grids

```
WALL SLIP [ITERATIONS] val [zone_selector]
```

To minimize transients at the start of a Wind-US calculation, with structured grids the velocity at no-slip boundaries is actually reduced from its initial value to the no-slip condition over a number of iterations. The `WALL SLIP` keyword allows the user to specify the number of iterations, given by *val*, on a zonal basis. The default value is 50 iterations.

WALL TEMPERATURE — Specify wall temperature

```
WALL TEMPERATURE {ADIABATIC | value} [zone_selector]
```

This keyword allows you to specify a wall temperature on a zonal basis.

`ADIABATIC` Use an adiabatic wall boundary condition for temperature. This is the default if the `WALL TEMPERATURE` keyword isn't used.

value Use a constant wall temperature equal to *value* °R. Zero-gradient extrapolation is used to get the chemical species at the wall for finite rate chemistry.

See Also: `TTSPEC`

11 Test Options

Several user-controlled options have been provided as an aid to modifying Wind-US. These options all may be selected by using the keyword `TEST` in the input data file. The test options typically control program features which are under test, and have not been accepted for production use. Each test option is of the form

`TEST` *number mode*

If *mode* is not described for a given test option, the user should use *mode* = 1 to activate that option.

As test options are accepted, they are "hard wired" into the code and the test option described here becomes meaningless. Test options may also be rejected based on trial runs. In that case, the option code described here will also become meaningless. For this reason, the list of valid options is not consecutive. Selection of an invalid option will be accepted by Wind-US, but will have no effect.

The various test options and modes are described in Table 4. For each option, the subroutines referencing that option are listed in parentheses.

Table 4: Non-Production Test Options

number	**Description**
2	Designed for parallel processing data transfer debugging *mode* Result 1 Not used 2 Don't read zonal boundary data (`evrwbd`) 4 Don't solve zone (`evsolv`) 8 Don't write zonal data (`evwzon`) 16 Don't write zonal boundary data (`evrwbd`) 32 Not used 64 Not used 128 Not used 256 Don't update boundary conditions (`lpschm`) Set *mode* equal to the sum of the desired actions.
3	Parallel processing task tracing *mode* Action 1 Trace event reads/writes (`rwev`) 2 Trace file I/O (`rwnh, rwd, rwi, rwr`) 4 Trace network traffic (`psexit, psrwev, psrwgv, psrwnh, psrwd, psrwi, psrwr`) 8 Trace task begin/end (`psspwn, tskbeg, tskidl`) 16 Print task queue for debugging (`psqprt`) Set *mode* equal to the sum of the desired actions. I.e., setting *mode* = 5 will trace both event reads/writes and network traffic.

Continued on next page

Table 4: **Non-Production Test Options** (*Continued*)

number	Description
4	Sets `ifCellCntrd` = *mode* for all zones (`opngrd`)
5	Compute the L2 norm of the residual for the Navier-Stokes equations in the same way as the "old" code (`l2norm1d`)
6	Write *.cfl* file compatible with the "old" code (`asnsx, asvisc`)
7	Do not use high performance C I/O interface (`openf`)
8	Use Version 2 common files (`mpinit, openf`)
9	For *mode* = 1, run a verification case using the method of manufactured solutions. If *mode* = 2, in addition to running the case, Plot3d function files named *mms.exact.fxn*, *mms.cfd.fxn*, and *mms.error.fxn* are written containing the exact solution, the Wind-US solution, and the error. The functional forms for the primitive variables are combinations of sine and cosine functions, and are coded in subroutines `mms_3d_euler_bc` and `mms_3d_ns_bc` for the Euler and Navier-Stokes equations, respectively. The corresponding source terms for the governing equations are coded in subroutines `mms_3d_euler_src` and `mms_3d_ns_src`. The choice of an Euler or Navier-Stokes solution is determined by the `TURBULENCE` keyword. If the flow is inviscid in all zones, an Euler solution is computed; otherwise, a constant-viscosity laminar Navier-Stokes solution is computed. The flow may be 2-D or 3-D, as determined by the grid file. Multi-zone grids may be used, but the use of `COUPLING MODE CHARACTERISTIC` is recommended for Navier-Stokes solutions. (Viscous terms are neglected in Roe boundary coupling, and they are *large* in the method of manufactured solutions.) Frozen boundary conditions must be specified in the grid file at all non-coupled boundaries. The appropriate boundary conditions for the functional forms being used will then be set automatically. See Roach (1998) and Salari and Knupp (2000) for more detailed information on the method of manufactured solutions. (`l2norm1d, lpschm, mms_test_soln, nsrhss, pstinp, sins, tdbcni`)
10	Print the time step information (i.e., minimum/maximum CFL and Δt) into the *.lis* file every *mode* cycles, instead of just on the first cycle. (`zsolv`)
17	Use "new" Baldwin-Barth turbulence model (`bbarth`)
20	Non-dimensionalize k and ω in the SST model the "old" way (`aijkrg, aikeps, sst1, sstprtinp, sstpstprt`)

Continued on next page

Table 4: **Non-Production Test Options** (*Continued*)

number	Description
21	Spalart-Allmaras turbulence model. (See the `TURBULENCE` keyword.) (`redimsa, sabound, saprtinp, sapstprt, sinut, spalart`) *mode* Result 0 Use original 1992 model, with an f_{t2} term for laminar stabilization and a default freestream value for ν_t of 5.0. 1 Like mode 0, except with “corrections” to the production and destruction terms. This is equivalent to the default model for WIND beta versions 4.15 to 4.92. 2 Like mode 1, except without the f_{t2} term, and with a default freestream value for ν_t of 0.1. In addition, the initial value of the dependent variable $\tilde{\nu}$ is set to the freestream ν_t. This is equivalent to the default model for WIND versions prior to WIND beta 4.15, and includes a slight error that makes the model overly dissipative.
25	In the Baldwin-Lomax model, use y^+ based on wall vorticity (`blomax`)
26	Use local values in y^+ damping for the Baldwin-Lomax, Cebeci-Smith, Baldwin-Barth, and k-ϵ models (`bbdamp, blomax, cebeci, kepy2`)
29	For the Cebeci-Smith model, use y^+ based on wall vorticity. (`algtur, cebeci`) For the k-ϵ models, `TEST 29` is a production limiter (`kelhssch, kelhssrg, keprod, kerhssch, kerhssrg, redimkeps3d`) *mode* Result 0 Production limited to 20 × dissipation 1 Production computed from vorticity, but not limited 2 Production not limited 3 Production computed from vorticity, then limited 4 Production computed using $2\mu_t S_{ij} S_{ij}$, but not limited 5 Production computed using $2\mu_t S_{ij} S_{ij}$, then limited Modes 4 and 5 only apply to the Rumsey-Gatski ASM k-ϵ model.
30	Irrotational boundary condition at freestream inflow boundaries (`bcfree`)
35	Flag for `LOADS` summary file (`frcsum`) *mode* Result 1 Write file in “old format” 2 Write loads on unstructured surfaces
37	In `wbnd2`, deallocate memory used for boundary coupling data before returning (`wbnd2`)
40	Old switch for compressibility correction in k-ϵ model; use `K-E COMPRESSIBILITY CORRECTION` instead. (`keppstin`)
46	In the SST turbulence model, in blowing regions and bleed regions with a specified negative bleed flow rate, set $\mu_{turb} = 10\mu_{lam}$ along the wall. (`sstbound`)

Continued on next page

Table 4: **Non-Production Test Options** (*Continued*)

number	Description
47	For the algebraic turbulence models, smooth turbulent viscosity in each *i*-plane using simple averaging. *mode* = number of smoothing passes. (`smtvis`)
48	For the algebraic turbulence models, smooth turbulent viscosity in three dimensions using simple averaging. *mode* = number of smoothing passes. (`smtvis`)
49	Modified Runge-Kutta smoothing (see the `SMOOTHING` keyword) (`bdload, dampi, dampj, dampk`) *mode* Result 2 No pressure switch on second-order dissipation 3 No pressure switch, and an LES type filtering of nonlinear terms
51	Limit the turbulent viscosity μ_T such that the maximum value of $\mu_T/(\mu_L)_\infty = mode \times 1000$. Suggested range is $50 < mode < 100$. Do not use this option with the k-ϵ models; use `K-E MAXIMUM TURBULENT VISCOSITY` instead. (`keppstin, mutlim`)
52	When using `BLOW PLENUM`, print a warning when the plenum total pressure is automatically raised because it was less than the local static pressure (`bcbled`)
53	Allows no-slip in inviscid flow at "viscous wall" boundaries (`bcslip`)
54	Reserved for use at Boeing
55	Reserved for use at Boeing
56	No energy addition to fluid due to MFD equations (`emdef`)
57	Implicit terms on for the Spalart-Allmaras and SST turbulence models (`spalart, sst1, sst2`)
58	Store the Lorentz force in the *.cfl* file instead of the electric field (`emdef`)
59	Apply `SMOOTHING` keyword values to the Spalart-Allmaras model as well as the mean flow solver. (Currently deactivated) (`spalart`)
60	Print warning when local and coupled normal velocities have inconsistent directions at a coupled boundary (`postrbs`)
61	When *mode* = 2, all boundary conditions are applied, whether or not they're consistent with the `IBLANK` values. This only affects corners, where there are usually multiple boundary conditions. So, if a wall boundary at $j = 1$ meets an outflow boundary at $i = i_{max}$, if `TEST 61 2` is specified, both boundary conditions are applied. (`tdbcgs`)
62	Compute cell areas and volumes using procedure from WIND 4 (`nsrhsv, tdarea, vismet`)
63	Eliminate the "fat" boundary cells in any coordinate direction. *mode* = 1, 2, or 4 indicates the *i*, *j*, and *k* direction, respectively. Set *mode* equal to the sum of the desired directions. I.e., setting *mode* = 5 will eliminate the "fat" boundary cells in the *i* and *k* directions. (`nsrhsv, tdarea, tdarea2, vismet`)
64	Remove `dt` from `dq` when computing residuals (`l2norm1d`)
65	In marching solutions, lower the CFL number for the last marching step (`zsolv`)

Continued on next page

Table 4: **Non-Production Test Options** (*Continued*)

number	Description
66	Don't update β in gas3, for ireal $= 2$ and ispec $= 2$. This test option is not recommended but will decrease run time. (gas3)
67	Bleed/blowing boundaries in turbulence model solution (kebc, sabound, sstbound) *mode* Result 0 Treat bleed/blowing boundaries as no-slip walls. 1 Treat bleed/blowing boundaries as slip walls in the Spalart-Allmaras, Chien k-ϵ, and SST models. This was the default behavior prior to WIND 5.101. 2 Same as mode 0, except do not use the procedure of Wilcox (2000) to compute the boundary condition for ω in the SST model.
68	If the density is zero at a coupled boundary, issue a warning, ignore the coupling data, and continue. The default is issue an error message and abort. (postrbs)
70	Tolerance level for converging gas properties P, ρ, or T in the gas routines. Tolerance level $= (0.1)^{mode}$. (gas1, gas2, gas3, gas4)
71	Apply curve fit equations for thermodynamic properties even when the temperature is outside the applicable range. If *mode* $= 1$, an error message will be written whenever this occurs. For other non-zero values of *mode*, no error message is written. If this test option is not set, the run will be terminated if the temperature is outside the range of the curve fits. (cpfun, GasPTC, gibfn, Gtransp, hfun, P_Rho_RhoFi_2_T_E_G, P_T_Fi_2_Rho_C_G, P_T_Fi_2_Rho_E_G, Q_2_P_T_C, transp, ViscousFlux)
77	Set bleed limits for a specific F/A-18 15% scale sting and distortion model, for use with the BLEED AEDC keyword (bcaedc) *mode* Result 0 F/A-18E 1 F/A-18A
84	Use "old" viscous metric calculation (dsolv, vismet)
85	Check for zero volumes when computing viscous metrics (dsolv, vismet) *mode* Result 1 Check; if ≤ 0 print message and continue 2 Check; if ≤ 0 print message and stop
87	Freezes supersonic inflow at initial conditions (bcfreechar)
88	Bypass negative T check in tdgas. This is needed for chemistry if SHF (heat of formation) varies widely since we only have an old SHF to use to estimate T. (lpschm, tdgas)
89	Use "old" species flux correction method (gas1)

Continued on next page

Table 4: Non-Production Test Options (*Continued*)

number	Description
90	Chemistry stuff (`chinv`) *mode* Result 0 Analytic chemistry Jacobian (`ns` = 5 only) 1 Householder chemistry Jacobian (`ns` > 5) 2 Solves chemistry source term explicitly
91	Gas constant (`P_Rho_RhoFi_2_T_E_G, P_T_Fi_2_Rho_C_G, P_T_Fi_2_Rho_E_G, therm1, thermp`) *mode* Result 1 $\beta = \gamma = \beta_\infty$ 2 $\beta = \gamma = 1.4$
92	Utilize operator splitting for the reacting chemistry source terms to increase the stability of the integration, allowing more efficient solution of the coupled system. A 4th-order Pade approximation is used to integrate the reaction source terms, with *mode* setting the number of subiterations. Setting *mode* = 0 indicates no operator splitting. (`ChemSorc, chimplicit, chrhss, Gchimplicit, Relax110, Relax110_Pre`)
93	Turn on/off chemistry species diffusion (`chrhsv, rhsvfl, tdutv1, testprtinp`) *mode* Result 0 Include all chemistry species diffusion terms 1 Include chemistry species diffusion terms, except for the diffusion gradient in the conduction term 2 Same as 0 3 Ignore chemistry species diffusion
94	Turn off implicit chemistry terms (`tdimafk, tdimfu, tdimja, tdutaa`)
95	Turn off chemistry source term (`Grates, Grates1, Grates2, Grates3, Grates4, Gratesa, Gratesadl, Gratesb, Gratesf, rates, rates1, rates2, rates3, rates4, ratesa, ratesadl, ratesb, ratesf`)
96	Apply chemistry source term over *mode* iterations for finite-rate non-equilibrium chemistry (`ChemSorc, chrhss`)
97	P. D. Thomas turbulence model scanning direction. By default, Wind-US starts at viscous walls and moves into the field. This test option forces the code to calculate turbulent parameters from *any* boundary, in addition to walls. (`algtur`) *mode* Result 0 use j lines 1 use k lines 2 use j and k lines

Continued on next page

Table 4: **Non-Production Test Options** (*Continued*)

number	Description
98	*mode* is the relaxation factor for the species mass fraction from the Liu and Vinokur (real gas) model. By increasing *mode*, the mass fraction relaxes faster. Default *mode* = 5. *mode* = 1 corresponds to instantaneous. (`gas1, gas2, gas3, gas4`)
99	Initialize finite rate chemistry with Liu and Vinokur curve fits (`gas2`) *mode* Result 0 Do not track the species (valid to 50K?) 1 Track the species (valid to 10K?)
100	Characteristic time-stepping boundary condition (`bcfree, test100`) *mode* Result 0 Second order, with limit of $\Delta\mathbf{Q} \leq \mathbf{Q}/2$ 1 1st-order, original characteristic treatment 2 2nd-order, original characteristic treatment 3 1st-order, Roe's average characteristic treatment 4 2nd-order, Roe's average characteristic treatment
102	Use time-averaged back pressure for mass flow boundary condition (`pdsmfr`)
103	At unstructured grid boundaries where characteristic boundary conditions are applied (i.e., freestream boundaries, and outflow boundaries for which no "downstream" keyword is specified), and `HOLD TOTALS` is specified, don't abort when the static pressure exceeds the total pressure at the boundary. Instead, set the static conditions to the total conditions, and continue. (`Characteristics`)
104	Turn off implicit viscous terms (`rcutv1, tdutv1`)
105	Time step type (`iterprtinp, tdtmst`) *mode* Time Step Type 0 $\Delta t = \mathrm{CFL}/\max(\lambda_\xi, \lambda_\eta, \lambda_\zeta)$ 1 Flow angle scaling, $\Delta t = \mathrm{CFL} \times (f_\xi \Delta\xi + f_\eta \Delta\eta + f_\zeta \Delta\zeta)$, where $f_\xi = \sqrt{1 + \tan\theta + \tan\psi}$ $f_\eta = f_\xi \tan\theta$ $f_\zeta = f_\xi \tan\psi$ 2 Velocity scaling, $\Delta t = \mathrm{CFL} \times \min(f_\xi \Delta\xi, f_\eta \Delta\eta, f_\zeta \Delta\zeta)$, where $f_\xi = u/u_\xi/\lvert u_\xi + c\rvert$ $f_\eta = u/u_\eta/\lvert u_\eta + c\rvert$ $f_\zeta = u/u_\zeta/\lvert u_\zeta + c\rvert$ 3 $\Delta t = \mathrm{CFL} \times \min(\Delta\xi, \Delta\eta, \Delta\zeta)/(\lvert u\rvert + c)$ 4 $\Delta t = \mathrm{CFL}/(\lambda_\xi + \lambda_\eta + \lambda_\zeta)$
106	Compute the time step at the start of every cycle (even when Newton time stepping is being used), instead of at the start of every iteration. (`axflow, lpgrp, lpmg, redim`)

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Table 4: **Non-Production Test Options** (*Continued*)

number	Description
108	Extrapolate freestream outflow (`bcfree, bcfreebc`) *mode* Mach Outflow Conditions 0 < 1 Hold upstream running characteristic at freestream > 1 Extrapolate all, even in boundary layer 1 All Extrapolate all, even in boundary layer
109	Boundary flux treatment (`roewal, tdup1`) For `tdup1`: *mode* Result 0 Conservative 1 Upwind extrapolation from interior For `roewal`: *mode* Result 0 Characteristic inflow, conservation if flow parallel to wall 1 Characteristic regardless 1000 Use conservative wall treatment at all boundaries
110	Grid area variation limiting. Not allowed for `iorder` > 24, i.e., for the following Roe and Van Leer explicit operators: third-order fully upwind, fourth-order upwind-biased, fourth-order central, and fifth-order upwind-biased. (`roecof`) *mode* A_2/A_1 0 ∞ 1 2.0 2 1.5 3 1.33 4 1.1
111	Singular matrix check (`jacpr4, jacpr5, jacprg, jacprg4, tdsol4, tdsol9, tdsol11, tdsolg, tdsolg4, tdsolv`) *mode* Result 1 Check, but don't print results 2 Don't check
112	Corrected upwind scheme at boundaries. Defaults to corrected scheme, *mode* > 0 uses second order smoothing with *mode*/1000 as the smoothing level. Users should not use this option. (`rhsupw`)

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Table 4: **Non-Production Test Options** (*Continued*)

number		Description
113		Check for reverse flow at inflow and outflow boundaries (`bcconf, bcfree`)
	mode	Result
	0, 1	Print a warning message and continue
	2	Print an error message and stop
	3	Set velocity to zero and continue, with no warning message. This mode only applies at outflow boundaries (see Section 5.4.3).
114		Central difference ζ operator (`tdup1`)
	mode	Result
	0	Upwind
	n	Central smoothing coefficient $= n/1000$
115		Do not rescale inviscid wall total velocity to equal adjacent value, just subtract the normal component from the adjacent value (`bcvel`)
116		Set inward pointing normal to zero in `tdbcm1` at unknown grid topology points (`tdbcm1`)
117		Freeze inflow boundaries, even in subsonic flow (`bcfreebc, tst100bc`)
	mode	Result
	1	Freeze all inflow
	2	Freeze only arbitrary inflow points
	3	Freeze characteristics on all $i = 1$ boundaries
118		Singular axis fix (`radavg`)
	mode	Result
	0	Average density, momentum components, and pressure
	1	Average density, velocity components, and pressure
121		Under-Relaxation of points adjacent to singular axis (`bcpinw, bcsing, kebc, relsng, sabound, sngthrm, sstbound`)
	mode	Result
	0	Value on axis is a radius-weighted average of the values at the adjacent points; values at the adjacent points are unchanged
	n	Value on axis computed as for mode 1; values at the adjacent points are computed from $$F_{adj} = (1-r)F_{adj} + rF_{axis}$$ where F_{adj} is the value at the adjacent point, F_{axis} is the axis value, and $r = n/1000$.
122		Allow left-handed coordinates (`tdarea1, tdarea2`)
123		Track back pressure, mass flow, and integrated total pressure with outflow boundary conditions (`bcconf, MassFlux, pdsmfr`)
124		Write convergence information to list output (*.lis*) file every iteration instead of every cycle (`lpschm`)

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Table 4: **Non-Production Test Options** (*Continued*)

number	Description
126	Compressibility correction to Baldwin-Lomax turbulence model (`blomax`) *mode* Result 0 No compressibility correction 1 $\kappa = 0.0180$ for Baldwin-Lomax model (CFL3D uses this)
127	Scale printed residual by maximum residual over all time steps (`lpschm`)
128	Check the L2 norm of the residual for convergence instead of the maximum residual (`l2norm1d`)
131	For boundary layers on $j = 1$ walls, set the time step in the boundary layer to a (larger) "outer" value, defined as the value at $j = mode$. I.e., $(\Delta t)_j = (\Delta t)_{mode}$ for $j < mode$. (`tdtmst`)
132	Renormalize, changing from total to static values. Normalizing values in the *.cfl* file are unchanged. (`redim`)
133	Print multi-grid sub-iteration convergence data (currently deactivated) (`lpschm`)
134	Second order characteristic extrapolation for adjacent conditions (`bcptcond`) *mode* Result 2 First order 0, 1 Second order, using a minmod limiter
135	Resets the time step using a weighting function between the ordinary Euler CFL number and a new "viscous CFL number", for convergence acceleration in viscous layers. The viscous CFL number is set to *mode*/1000. Limited testing indicates that a value of $mode = 50$ is stable and increases the time step near the wall by at least an order of magnitude. (`tdtmst`)
136	Divergence checker, $mode = n_1 + 10n_2$, where (`lpgrp`) n_1 Divergence Definition 1 Max residual > 1.0, L2 norm increasing 2 Max residual > 5.0, L2 norm increasing 3 Max residual > 10.0, L2 norm increasing and n_2 Action Taken When Diverging 1 Terminate iteration for current cycle 2 Abort run 3 Reduce CFL number by 1/2 4 Reduce CFL number by 1/2 and terminate iteration for current cycle

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Table 4: **Non-Production Test Options** (*Continued*)

number	Description
137	Butt line interpolation region for USERSPEC; smear USERSPEC conditions over 0.001 × butt line at minimum and maximum butt line (`uspeci`) *mode* Result 0 No interpolation n $n = 0.001 \times$ butt line for interpolation
138	Use large cell Jacobians at boundaries (`bcwall, chrhsv, nsrhsv, tdarea, tdarea1, tdarea2, vismet`) *mode* Result ≤ 1 Use large cells 2 Use large cells, central difference Jacobian 3 Throw out half cell at boundaries 5 Solve $\partial P/\partial n$ equation at walls
139	Turn on grid-based flux limiter (`tdup1`)
140	Use first-order differencing for computing $\partial(u,v,w)/\partial\xi$ term in vorticity used in turbulence models (`vortcy`)
141	2nd-order wall boundary conditions (explicit) (`bcvel, bcwall`) *mode* Result 1 Second order $\partial p/\partial n$, $\partial T/\partial n$, and $\partial u_{tan}/\partial n$ 2 Second order $\partial p/\partial n$ and $\partial T/\partial n$, but not $\partial u_{tan}/\partial n$
147	?? (currently deactivated) (`turpdt`)
148	?? (currently deactivated) (`turpdt`)
150	Singular axis on symmetry planes. When symmetry plane test fails, zero this component of velocity. (`bcsing`) *mode* Result 1 $u = 0$ 2 $v = 0$ 3 $w = 0$ 4 do not zero any component (use average) 5 $v = w = 0$ 6 $u = w = 0$ 7 $u = v = 0$

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Table 4: **Non-Production Test Options** (*Continued*)

number	**Description**
151	For a singular axis, the value on the axis is a radius-weighted average of the values two points away from the axis, instead of the values at the adjacent points; values at the adjacent points are set to the average of the axis value and the value two points away from the axis. E.g., for a singular axis at $j = 1$, with the k direction "circumferential", the value on the axis is a radius-weighted average of the values at $j = 3$, instead of at $j = 2$. Then for each k, the value at $j = 2$ is set to the average of the values at $j = 1$ and $j = 3$. This test option overrides `TEST 121`. (`bcpinw, bcsing, kebc, kerot, radavg, relsng, sabound, sngthrm, sstbound`)
153	Iteration frequency for updating pressure at outflow boundaries. Default is 5. (`bcconf, MassFlux`)
154	When computing values at "undefined" boundary points, and no neighboring non-hole, non-fringe, points are found, average over neighboring fringe points. (`bcundef, kebc, sabound, sstbound`)
157	`USERSPEC` inflow (`uspeci`) *mode* Result 1 Put `USERSPEC` inflow at all points in the buttline range. Do not check for above/below vehicle. 2 Same as mode 1, but also ignore fuselage station check.
158	Write various unstructured grid info to *.lis* file (`Explicit, Implicit100, Implicit110, Implicit210, opngrd, ReadGrid`)
160	Pressure correction factor = *mode*/1000 for specified mass flow boundary (`MassFlux, pdsmfr`)
162	Cebeci-Smith boundary layer edge definition (`cebeci`) *mode* Result 0 1.0% change in U_{total} 1 0.995 H_t 2 0.99 U_{total} 3 0.9999 U_{total}
163	Criteria for defining F_{max} in Baldwin-Lomax model *mode* Result > 0 Search outward from wall; use first peak in F that is followed by a fractional decrease in F of *mode*/1000. < 0 Use the max F value between the wall and the $\|mode\|$'th grid point from the wall The default is +700. (`blomax`)
164	Iteration interval for updating gas properties and species for `ireal` = 1 and 2. The default value is 1. (`tdgas`)

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Table 4: **Non-Production Test Options** (*Continued*)

number	Description
165	Sets the tolerance for the distance between grid points used to determine a singular direction to $10^{mode/1000}$. The default is a tolerance of 10^{-8} (i.e., $mode = -8000$). (`bcsing, direct`)
168	For the algebraic turbulence models, begin turbulent flow at $i = mode$ (`tdvis1`)
170	NASA Ames time step formula. (CFL increases as $1/\sqrt{\Delta y}$ near the wall. Thus, Δt decreases as $\sqrt{\Delta y}$, not Δy as the default.) C_A is scalar coefficient on CFL; i.e., $\mathrm{CFL}_{wall} \propto C_A$. This test option has no effect if `TEST 105` mode 1, 2, or 3 is used. (`tdtmst`) *mode* C_A 1 0.01 n $0.001n$
172	Turn off base energy for `ireal` = 1 (`aichem, aijkrg, aikeps, ArbitraryInFlow, bcfreechar, Charact421, DqLimit, EnsightGama, EnsightMach, Explicit, GasPTC, gas1, gas2, gas3, gas4, gasint, ijkfreechar, pstinp, P_Rho_RhoFi_2_T_E_G, P_T_Fi_2_Rho_E_G, Q_2_P_T_C, Q_2_T_G, Q_T_2_G, redimchem, Resv405, stomp, tdimfp, tdroe4, Ttotalmdot, uspeci`)
174	For the algebraic turbulence models, the iteration interval for updating the turbulent viscosity. The default is 1. (`tdvis1`)
175	Boundary conditions at freestream radial outer boundaries (`nzn` = −6). (`bcfree, bcfreechar`) *mode* Result 0 Compute characteristics from freestream conditions 1 Compute characteristics from conditions at $i = 1$ along boundary 2 Extrapolate without testing at k boundaries; treat i and j boundaries as in mode 1
177	Freeze maximum residual (`lpgrp`)
178	Insert freestream species buffer during `BLOW VALVE` relaxation (`bcbled`)
179	Modify solidbody rotation radius to get linear swirl profile in r, but with zero velocity not at center of rotation. $mode = 1000r_0$, where r_0 is the radius (from the point x_c, y_c, z_c specified using the `SOLIDBODY` keyword in the `ARBITRARY INFLOW` keyword block) for zero velocity. (`rotat`)
180	Defines the radius of the solidbody rotation core for actuator disk free vortex modeling. $mode = 1000r_{core}$, where r_{core} is the solidbody core radius. (`rotat1`)
182	?? (`tdbcgs`)
185	?? (`gasint`)
187	$mode/1000$ = factor for suppression of streamwise pressure gradient when marching. The default is 950, and values below 800 are not recommended. When separation or strong adverse pressure gradients are causing problems, values between 800 and 900 will really help. (`rhsmar, tdimfp`)

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Table 4: **Non-Production Test Options** (*Continued*)

number	Description
189	If a first-order upwind explicit operator modified for stretched grids is used (e.g., `RHS ROE FIRST PHYSICAL`, then `TEST 189 1` must also be specified. (`numprtinp`)
190	Outgoing wave Roe boundary treatment (`pstinp, roecof, roeht, tdbcgs`) *mode* — Result 0, 1 — Use normal Roe boundary treatment (uses boundary point in formulation) 2 — Lower order by one (does not use boundary point in formulation). This option cannot be used with `TVD` in the same zone. 3 — Use zero-order extrapolation
192	Save metrics in a temporary file. After the first cycle, metrics will be read rather than computed. This eliminates the CPU resources required to re-compute the metrics each cycle, but adds significant I/O to the computation. In the past, on at least some Cray systems, this reduced the CPU time by approximately 40.8 μsec/(node-cycle). On the more common platforms, however, it is generally faster to re-compute the metrics rather than store them. (`lpcycl`)
193	Do *not* stop if a singular line is encountered normal to a wall (`bbdamp, blinit, kepy2`)
194	Bypass singular viscous metric check (`dsolv, vismet`)
195	When using `BLOW SURFACE`, print a warning when the flowfield static pressure becomes larger than the plenum total pressure, causing blowing to be turned off at that point. Note that this is a five-line message written for each iteration and each "closed" node, and could cause the *.lis* file to become very large very quickly. (`bcbled`)
196	Overlapping grid: print an error message if there are no points adjacent to a fringe point (`srfpar, tdbcgs`)
197	Roe self-coupling mode (`pstinp`) *mode* — Result 0 — Once per iteration, using `bcself` 1 — Once per cycle, using standard zone coupling
198	Sets the tolerance level for fuselage station `USERSPEC` inflow to *mode*/1000. The default tolerance is 0.01 (i.e., *mode* = 10). (Currently deactivated) (`uspeci`)
199	Singular axis averaging — average from 1 to ($max - 1$), *not* 1 to *max*. (`bcsing, linzero, radavg, relsng, sngthrm`)
200	Don't bomb for negative speed of sound in `tdroe3` (`tdroe3`)

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